THE BOOK OF THE SEXTANT

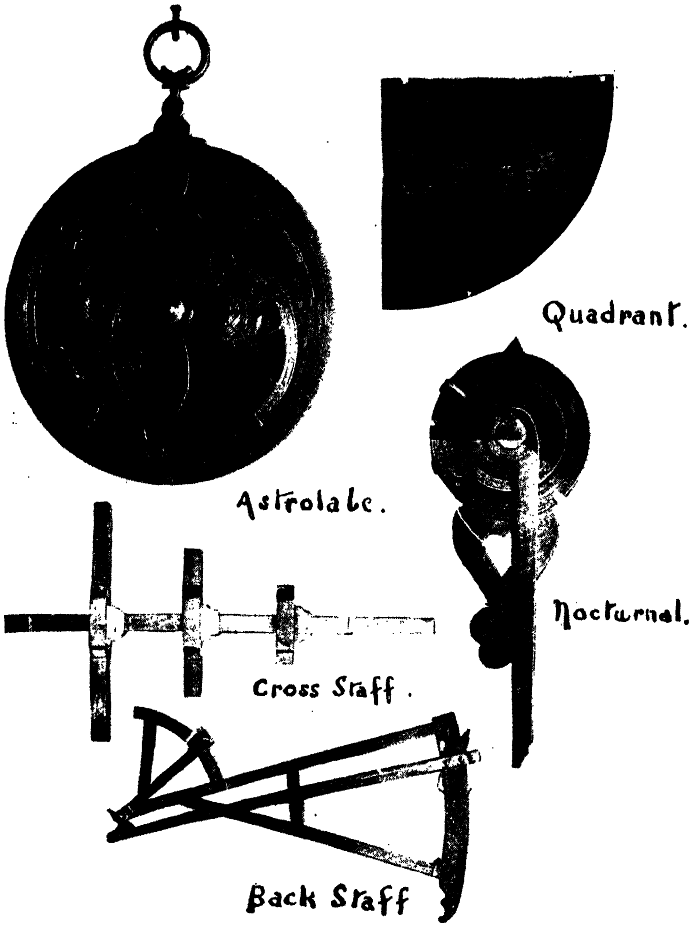

Fig. 1.—OLD INSTRUMENTS.

The Book of the Sextant

WITH

Ancient and Modern Instruments of Navigation

BY

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INTRODUCTION

The knowledge of the positions of the heavenly bodies with reference to the earth enables the observer on the terrestrial sphere, when provided with suitable instruments, to ascertain his position with considerable accuracy by observations of these bodies. By means of certain calculations based on spherical trigonometry, the latitude and longitude can be obtained from the altitude and bearing of such heavenly bodies as may be available and suitable. Whilst the bearing of the body has a certain importance in these calculations, the altitude and its measurement are the paramount considerations in the observations.

When a steady platform is available, a comparatively simple instrument can be produced to measure this altitude. The instrument can be levelled by means of cross-level bubbles, and the angle between this horizontal level and the body can be measured by suitable graduations in conjunction with a sighting device. The theodolite is an example of this type of instrument.

The mariner has always been very interested in the question of position finding, but the nature of the element on which he travels necessitates the use of an instrument of a design different from that of the theodolite. Two paths seemed to be open to the designer when he entered into the question of producing a suitable instrument for use at sea: (1) the instrument had to be so designed that it would indicate the horizontal, no matter what the motion of the ship might be; or (2) the instrument had to be designed to measure the angle between some definite datum and the body, the obvious datum being the visible horizon. Early designs on the first of these principles failed to attain to a sufficient degree of accuracy, and attention was turned to the second. The chief source of trouble

lay in the fact that, in order to get accuracy, the observer had to see both the horizon and body coincident and simultaneously, a feat of considerable difficulty in the early models. Finally, early in the 18th century, a true reflecting instrument was produced which was the fore-runner of the modern marine sextant.

Many attempts have been made to produce an instrument which would obviate the use of the sea horizon as the datum, and most successful of these has been the bubble horizon. The marine navigator has long felt the need for an instrument which will give him reasonably accurate observations for use when sea horizon conditions are poor, and the demands of the air navigator have emphasised this. If an aircraft is operating at very moderate heights over the ocean, the percentage of days on which visibility is such that the sea horizon is clear enough for use is very small, and this is reduced much further as the height of operation is increased. The use of the marine sextant for air navigation is thus precluded, unless the instrument is fitted with some type of artificial horizon and, as a result, an instrument of a very different design has been produced for air work. Observations made in the air by means of such an instrument do not attain to the degree of accuracy reached by those made with the marine sextant using the horizon as the datum, but as the requirements of the air navigator are not as precise as those of the mariner, the instrument, with certain modifications, has been used with marked success. The mariner faced with a clear sky but hazy horizon should be able to obtain very reasonable results from an instrument of this type, but when the horizon is plainly seen it is the most satisfactory datum for the mariner.

The possibility of inaccuracies arising in a single observation taken with a bubble horizon led to experiments in averaging devices, by means of which the observer was relieved of the necessity of reading each observation, the mean of a given number of observations being read off directly at the end of the series.

The natural result of astronomical navigation in the air was the production of "quick method" tables and diagrams and mechanical devices for solving the navigational triangle. The probable reason for the comparatively few existing types of mechanical devices is the great accuracy of workmanship required in order to give the desired result, so that their production is not an economic proposition. A few of these devices will be described in later chapters.

The Book of the Sextant

CHAPTER I.

OLD INSTRUMENTS.

The Astrolabe.—The astrolabe is probably the earliest form of instrument designed for taking altitudes at sea, such as the altitude of the pole, the sun, or the stars. It was invented by Hipparchus, 160 B.C., and simplified by Stoleing, 187 A.D.

The common astrolabe consists of a large brass ring about 15 inches in diameter, whose limb, or a convenient part of it, is divided into degrees and minutes. It is fitted with a moveable label or index which turns upon the centre and carries two sights.

To make use of the astrolabe it is suspended on the thumb by the small ring at the top and turned towards the sun or heavenly body so that the rays may pass freely through both the sights; then the index will cut the altitude on the divided ring.

Gunter's Quadrant.—Gunter's quadrant, so called from the inventor, Edmund Gunter, consists of a quarter of a circle divided into 90° fitted with plane sights and a plummet suspended from the centre. It also has a stereographic projection of the sphere on the plane of the equinoctial, also a calendar of months next to the division of the limb.

To find the sun's meridian altitude for any given day, lay the thread to the day of the month in the scale next the division, then the degree it cuts is the sun's meridian altitude.

To find the hour of the day, having set the bead which slides on the thread to the sun's place in the ecliptic, observe the sun's

altitude by the quadrant, then if the bead be laid over the same on the limb it will fall on the hour required.

To find the sun's declination, bring the bead to the sun's place in the ecliptic, and move the thread to line of declination, when the bead will cut the degree of declination.

To find the sun's right ascension, lay the thread on the sun's place in the ecliptic, and the degree it cuts on the limb is the right ascension.

To find the sun's azimuth, set the bead for time as above, observe the sun's altitude, bring the bead to the complement of the altitude, and the position of the bead will give the azimuth sought among the azimuth lines.

The Nocturnal.—The nocturnal was an instrument chiefly used at sea for determining time by the rotation of the stars about the pole. There are several kinds of this instrument, some of which are projections of the sphere, such as the hemisphere or planisphere on the plane of the equinoctial. The seamen commonly used two kinds: the one adapted to the Pole Star and the first of the guards of the Little Bear, and the other to the Pole Star and the pointers of the Great Bear.

The nocturnal consists of two circular plates applied over each other. The greater, which has a handle, is about 2½-inch diameter, and divided into twelve parts answering to the twelve months, also each month is divided into every fifth day and in such manner that the middle of the hand corresponds to that day of the year in which the star inspected has the same right ascension with the sun. When the instrument is fitted for two stars the handle is made moveable. The upper circle is divided into twenty-four equal parts for the twenty-four hours of the day, and each hour subdivided into quarters. These twenty-four hours are denoted by teeth to be told in the night. In the centre of the two circular plates is adjusted a long index moveable on the upper plate, and the three pieces, two circles and index, are joined by a rivet, which is pierced through the

centre with a hole 2 inches in diameter through which the star is observed.

To use the nocturnal, turn the upper plate till the longest tooth marked 12 is against the day of the month on the upper plate, and, bringing the instrument near the eye, suspend it by the handle with the plane nearly parallel to the equinoctial, then, viewing the Pole Star through the hole in the centre, turn the index about till by the edge coming from centre you see the bright star or guard of the Little Bear, if the nocturnal is fitted for that star. Then that tooth of the upper circle under the edge of the index is at the hour of the night on the edge of the hour circle, which may be known without a light by counting the teeth from the longest, which is for the hour of twelve.

Cross Staff or Fore Staff.—Cross staff or fore staff, an instrument formerly used at sea for taking the altitudes of the heavenly bodies. It is so called because the observer in using it turns his face towards the object. The fore staff is formed of a straight square staff of about 3 feet long, having each of its four sides sliding upon it of unequal length, the halves of which represent the radii to the scales of tangents on the different sides of the staff. The first or shortest of these vanes is called the 10 cross or vane, and belongs to the 10 scale or that side of the instrument on which the divisions begin at 3° and end at 10°. The next longer cross is called the 30 cross, belonging to that side of the staff where the divisions begin at 10° and end at 30°. The third vane is called the 60 cross, and belongs to that side where the divisions begin at 20° and end at 60°. The last or longest vane is called the 90 cross, and belongs to that side where the divisions begin at 30° and end at 90°.

The chief use of the instrument is to take the height of the sun and stars, and the 10, 30, 60, or 90 cross is used according as the altitude is less or more; that is, if the altitude be less than 10° the 10 cross is used; if above 10° the 30 cross, and so on.

The Back Staff.—Back staff, an instrument formerly used for

taking the sun's altitude at sea, so called because the back of the observer was turned towards the sun when he made the observation. It was sometimes called Davis's quadrant, from its inventor, Captain John Davis, the celebrated navigator, who produced it about 1590.

The instrument consists of two concentric arches of boxwood and three vanes. The angles subtended by the arch of longer and shorter radius are 30° and 60° respectively, making between them 90° or a quadrant. The vane at the centre of the head of the instrument is called the horizon vane, that on the 60° arch the shade vane, and that on the 30° arch the sight vane.

To use the back staff, the shade vane on the 60° arch is to be set at an even degree with some altitude less by 10° or 15° than the complement of the sun's altitude is judged to be. The observer turns his back on the sun, lifts up the instrument and looks through the sight vane, raising or lowering the quadrant till the shadow of the upper edge of the shadow vane falls on the upper edge of the slit in the horizon vane; then, if he can see the horizon through the said slit, the observation is exact and the vanes are rightly adjusted; but if the sea appear instead of the horizon the sight vane must be moved downward, or if the sky appear it must be moved upwards. The observer then reads how many minutes and degrees are cut by the edge of the sight vane, and to them he adds the degrees cut by the upper edge of the shade vane. The sum is the sun's distance from the zenith or the complement of its altitude.

The first true reflecting instrument was invented by John Hadley in 1730. The instrument consists of the following parts:—An octant or eighth part of a circle, the index, the speculum, two horizon glasses, and a set of coloured shade glasses and two sight vanes. The arc is graduated to 90°.

The original pattern of this instrument was generally made about 18 inches radius of mahogany or ebony with ivory arc. As time went on it was gradually reduced in size, and with the exception of the back sight by which a back observation was taken and which is not now fitted, it is practically the same instrument as is generally in use at the present time.

CHAPTER II.

PRINCIPLES OF THE SEXTANT.

First Principle.—The angle of incidence equals the angle of reflection in a plane which contains the normal to the reflecting surface at the point of reflection.

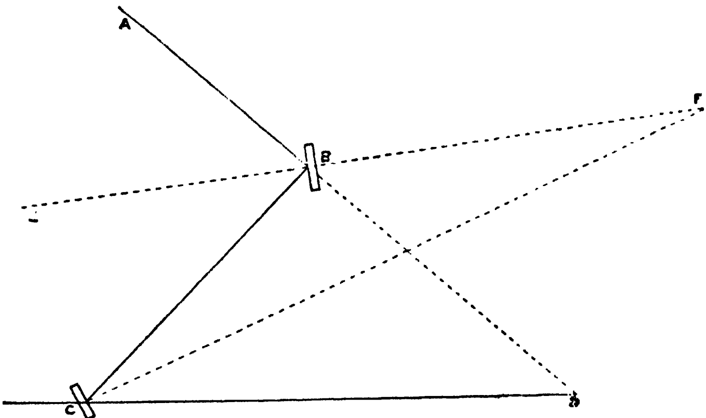


Fig. 2.

Let B and C represent the index and horizon glasses.

$E\ B\ F$ is the normal or perpendicular to B.

$C\ F$ is the normal or perpendicular to C.

$A\ B$ is the ray of light falling from the star on the index mirror B.

$B\ C$ is the path of reflection from the index mirror to horizon mirror.

$C\ D$ is the final course of the ray reflected from the horizon mirror to the eye.

Then by the first principle $\quad A\ B\ E = E\ B\ C$

and $\quad B\ C\ F = F\ C\ D$

Second Principle.—If a ray of light suffers two successive reflections in the same plane, by two plane mirrors, the angle between

the first and last direction of the ray is twice the angle between the mirrors.

Then ADC, which is the angle between the first and last direction of the ray $ABCD$, is by geometry—

$$
\begin{aligned}
& ABC - BCD \\
& ABC = 2EBC \\
& BCD = 2BCF \\
\therefore\quad & ADC = 2EBC - 2BCF \\
& = 2(EBC - BCF) \\
& = 2BFC \\
& = \text{twice the angle between the mirrors.}
\end{aligned}
$$

The application of *the principles* to the Air Sextant.

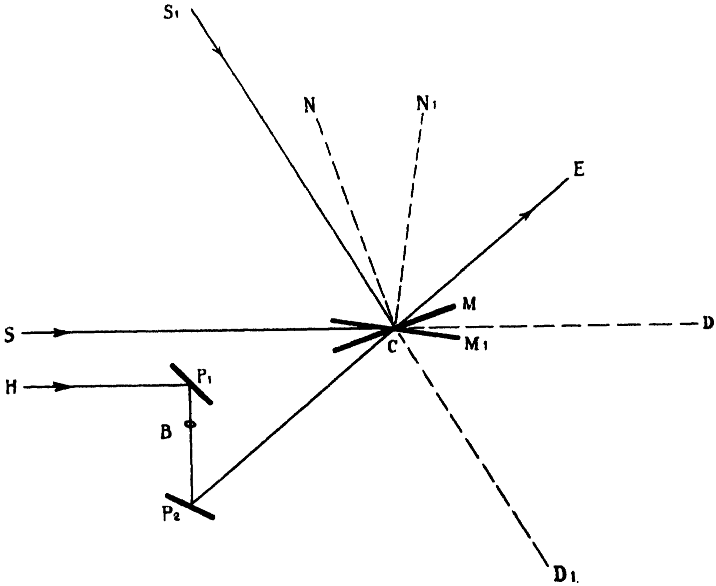


Fig. 3.

M is a transparent mirror which can be pivoted about C in the vertical plane.

E is the observer's eye.

P_1 and P_2 are reflecting surfaces of prisms.

B is a bubble formed in a transparent chamber.

When the instrument is held so that $H\ P$ is horizontal, the bubble will take up a position in the centre of its run. A ray of light will pass from H, be reflected by P_1, pass through the bubble, be reflected by P_2 through the mirror to E. A ray of light from S will be reflected by the mirror to E, and when the mirror is correctly positioned, this ray will be coincident with that which passes through the bubble chamber. The rays $H P_1$ and $S M$ are parallel if their mutual source is at infinity. The angles $S\ C\ N$ and $N\ C\ E$ are equal, $C\ N$ being the normal to the mirror, and the angles being those of incidence and reflection respectively. If E is maintained in the same position, and the mirror is turned to position M_1, then S must be moved to S_1 in order that the ray of light may still appear coincident with that from H when viewed from E.

$$S\ C\ E = 2\ N\ C\ E$$
$$S_1 C\ E = 2\ N_1 C\ E$$
$$\therefore\ S\ C\ S_1 = 2\ N\ C\ N_1$$

but the angle $N\ C\ N_1$ is the angle between the normals to the mirror in its two positions and is therefore the angle through which the mirror has been turned. Therefore, the angle through which the mirror is moved, $N\ C\ N_1$, is half the angle through which the source S has moved.

A very important point arises when the sextant, either marine or air, is moved slightly in the plane of the light rays. In the marine sextant the ray from the horizon will pass through a different part of the horizon glass and enter the telescope at an angle. The ray from the body to be observed changes its direction by twice the angle between the two mirrors, and as these have not been moved relatively to each other this ray is still coincident with that from the horizon. The total effect has been to move the coincident horizon and body rays slightly up or down. In this case the difference of the number of reflections in the index and horizon rays must be zero or an even number.

In the case of the air sextant this difference will depend upon

whether the bubble is seen directly from above or by reflection from below. In the former case the difference should be an odd number; and in the latter the difference should be either zero or an even number.

CHAPTER III.

CONSTRUCTION OF THE MARINE SEXTANT.

The Limb A.—The frame of the sextant is called the limb and is constructed of a bell metal alloy containing 7 per cent. of tin. In order to give rigidity to the framework, it is essential that the limb should be incapable of bending, as even a small flexure will produce large errors. The design of the framework is therefore very important, and only those patterns should be selected which ensure a proper rigidity.

The three circle, the diamond, the triangle, are all well-known patterns of framework which have stood the test of time. Several instruments of these patterns have been re-tested at the National Physical Laboratory and have given the same errors all along the arc after 50 years of hard wear.

Sextants are sometimes made of an alloy of aluminium for lightness, but that is not a great advantage, as a certain amount of weight gives steadiness. Four pounds weight has been found the maximum for comfort in taking observations.

The arc of the sextant on which the divisions are made is inserted in the sextant limb and the face turned flush. The arc is of silver. The dividing is arranged to indicate twice the angle through which the index bar and mirror are rotated; it therefore gives a direct reading of the angle measured and avoids having to multiply by two.

The Index Bar B is of flat sheet brass, into one end of which the centre is fitted in a central hole and secured by three screws, and above which is fixed the index clip. The other end of the

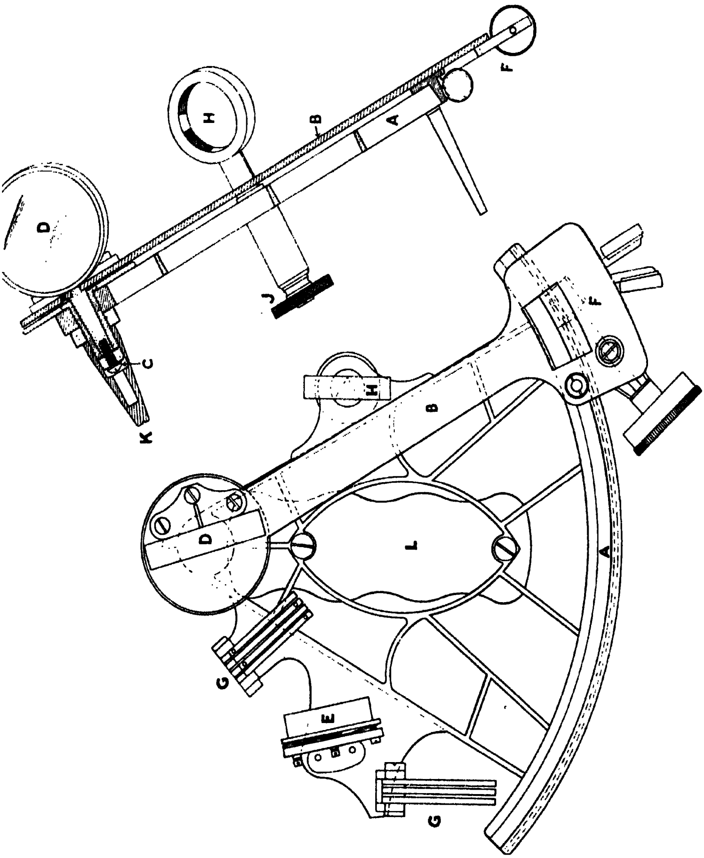


Fig. 4.—DIAGRAM OF SEXTANT.

index bar carries the tangent gear *F* for moving the bar along the arc, and also the micrometer gear for reading the angle observed. This gear replaces the old tangent screw and clamp, which have practically disappeared from the modern sextant design. An index is provided on the index bar by means of which the whole degrees are read from the graduated arc. On the periphery of the arc are cut the teeth of a worm gear and the worm shaft carries a

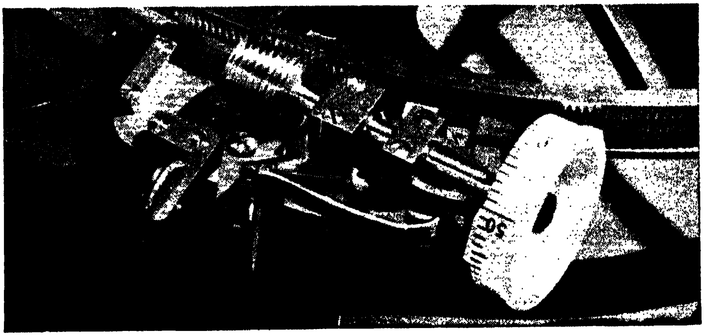
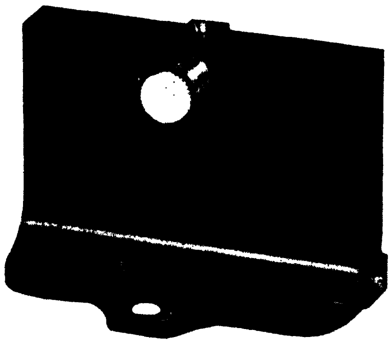


Fig. 5.

graduated head which shows the minutes of arc against another index. The mechanism is provided with a means of rapid movement in which the spindle is disengaged from the toothed arc. The teeth are cut so that one tooth corresponds exactly to one degree change of altitude, consequently the zero of the minute scale on the graduated head is not affected by any rapid movement obtained by disengaging the worm.

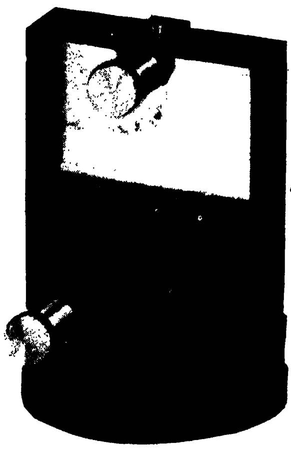
Centre and Socket C.—The centre work of a sextant requires special attention. The centre socket of brass, after boring and broaching, is ground on a hard steel arbor, so ensuring a straight and clear round hole.

The centre, which is of specially hard metal, is turned in a precision lathe nearly to a fit. It is then ground to a fit by means of fine stone powder and finished with pencil dust. The fitting hole in the limb for the centre socket also requires special attention.



D

Fig. 6.—INDEX GLASS AND CLIP.



E

Fig. 7.—HORIZON GLASS AND CLIP.

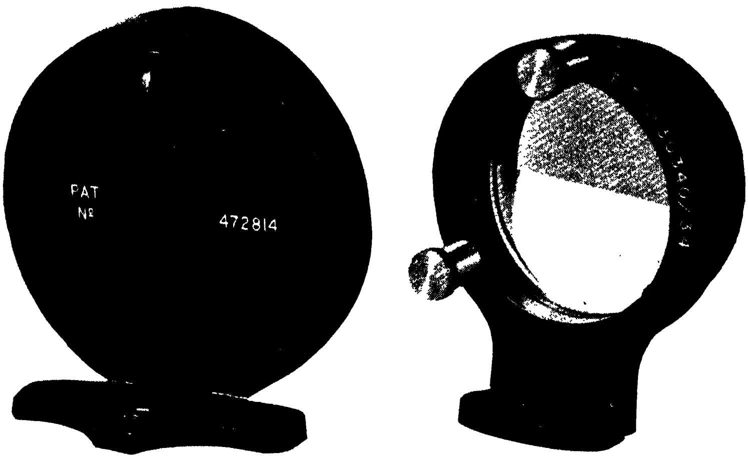
The limb, after being turned, is tested on a true surface plate before the hole to receive the socket is turned out, thus ensuring the axis of the hole being at a perfect right angle with the plane of the limb and that the index arm will move parallel to the limb.

The Index Glass and Clip D.—The index glass is a plane mirror with its two faces ground parallel and the one silvered. It is set in a brass frame fitted over the centre of motion of the index bar. Its face is perpendicular to the plane of the instrument and an adjusting screw in the base of the clip protected by a cover provides the means of setting the glass perpendicular.

The Horizon Glass and Clip E.—The horizon glass is a plane mirror with only one half of the glass silvered, the other half being left clear for the direct vision of the horizon. The clip consists of a brass frame securely fitted to the frame of the sextant with two adjusting screws at the base of the clip, one for adjusting the horizon glass perpendicular to the plane of the instrument, and the other for adjusting the horizon mirror parallel to the index mirror. They are fitted in such a way that no pressure is brought to bear on the glass. A light screen covers the adjusting screws. Some sextants are made with the adjusting screws placed on the back of the clip with brass covers, but this way is more awkward to adjust and is liable to put a torsion on the glass.

Round "Silex" Mirrors.—The mirrors of new sextants are coated with pure metallic silver by a chemical deposit process; the silver is then further protected by plating it with copper and again painting this with bronze paint. These mirrors are rectangular in shape, silvered all over as regards the index mirror, whilst the horizon mirror is silvered all over during its preparation and then part of the silvering is removed. Many sextant repairers still use the old process of "silvering" by the mercury and tinfoil process. Either method will do when a mirror requires silvering, but the sextant maker always prefers the real silver or so-called hard silver

process. The most active agent causing deterioration of sextant mirrors is salt, consequently the sextant should be protected from sea-spray and carefully wiped after any exposure. Owing to the small space between mirror and mirror frame which is provided for movement of the mirror when adjusting, spray which has found its way into this crevice cannot easily be removed and it is thus left to attack first the protective coating and finally the silver which it guards. The most sensitive places are obviously the corners of the mirrors and the "cut" or line where the silver has been removed



D Fig. 8. E

from part of the horizon glass, which is by far the most sensitive. The obvious remedy was to prevent the access of spray to the silvering, and the production of the access of spray to the silvering, and the production of hermetically sealed mirrors seems to have supplied the remedy. These mirrors are silvered, copper-plated and painted with special resistance paint, and are then mounted in such a way that all access of air to the silvered and protected reflected surface is completely excluded, so that no spray can possibly get in to produce ill-effects. These mirrors are circular in shape to permit the use of the special cell required to obtain the hermetic seal.

The cell or mount is in three parts, the base or back plate, by means of which it is attached to the sextant, the rubber seal and the screwed cap. The rubber seal of the same diameter as the mirror is laid on the back plate and covered with the mirror, silvered side down. The screwed cap is then screwed on to the thread on the back plate, so that the mirror is pressed up against the lip of the screw cap by the rubber seal. Little, if any, air can get past the contact of mirror and metal cap, and none at all can penetrate through the rubber seal to reach the silvering on the under surface. As the rubber seal, to be efficient, must seal off the whole area on which the silver has been deposited, it is necessary to use a horizon mirror having its surface silvered all over, and this results in the line of demarcation between true and reflected images being the arc of a circle instead of the usual straight line. This is objected to by some navigators, and further investigation led to the production of hermetically sealed mirrors having the normal straight cut. These mirrors are made by first preparing a circular plano-parallel glass, and covering half the surface with silver in the usual manner but without any protection. A second similar unsilvered plano-parallel glass is then cemented on to the silvered side of the first glass with transparent optical cement, special precautions being taken to keep both glasses perfectly parallel to each other. Such a mirror has the straight "cut" favoured by the navigator, whilst it is hermetically sealed against the action of the atmosphere by the cemented covering glass.

The Shades G.—The shade screens are of large size to ensure no naked rays from the sun passing through the horizon glass to the eye, which is important in making a clear observation. They are mounted in brass frames attached to the frame of the sextant in front of the index glass and behind the horizon glass, and consist of well selected shades of neutral glass.

The Telescope Holder H.—The telescope holder or rising piece consists of a brass ring fitted in another collar with a square or

triangular stem which slides up and down in a socket fitted in the limb just opposite the horizon glass. The telescope is screwed into the first collar, which is provided with two adjusting screws for setting the axis of the telescope parallel to the plane of the sextant. The collar and telescope can be raised or lowered by means of a large milled head J at the end of the socket, thus bringing the optical centre of the telescope opposite any part of the horizon glass in a line parallel to the sextant plane. This is the arrangement by which relative brightness of the reflected and direct image is regulated. The first collar is sometimes made with three segments of the thread cut out so that the telescopes can be quickly inserted with arc turn only. A stay or strut should be fixed from the telescope holder socket to the hollow leg K in order to prevent errors arising from any pressure being put on the telescope or its socket.

The handle *L* is usually of hard wood, ebony or cocus, fitted at the back of the sextant. The best form is the bridge handle, which has a bridge with two screws for attaching it to the limb at each end of the handle.

Sextant Case.—A sextant case should be of well-seasoned wood polished inside and out. It should be sufficiently large to take the star telescope focussed as well as the sextant with its index clamped to any division on the arc between 0° and 100°. The packings in the case should be secured with screws and include a camel's-hair brush and screw driver. A brass folding countersunk handle with hooks and studs and good lock is also provided.

Dividing.—The most important operation in the making of a sextant is the cutting of the arc. This is done on a dividing machine, which consists of a large surface plate, revolved by an accurate micrometer screw attached to a ratchet wheel and pulley. The dividing point is fixed in a swinging arm mechanically controlled and so brought to the right cutting point both vertically and horizontally.

The sextant limb is laid flat on the surface plate and centred.

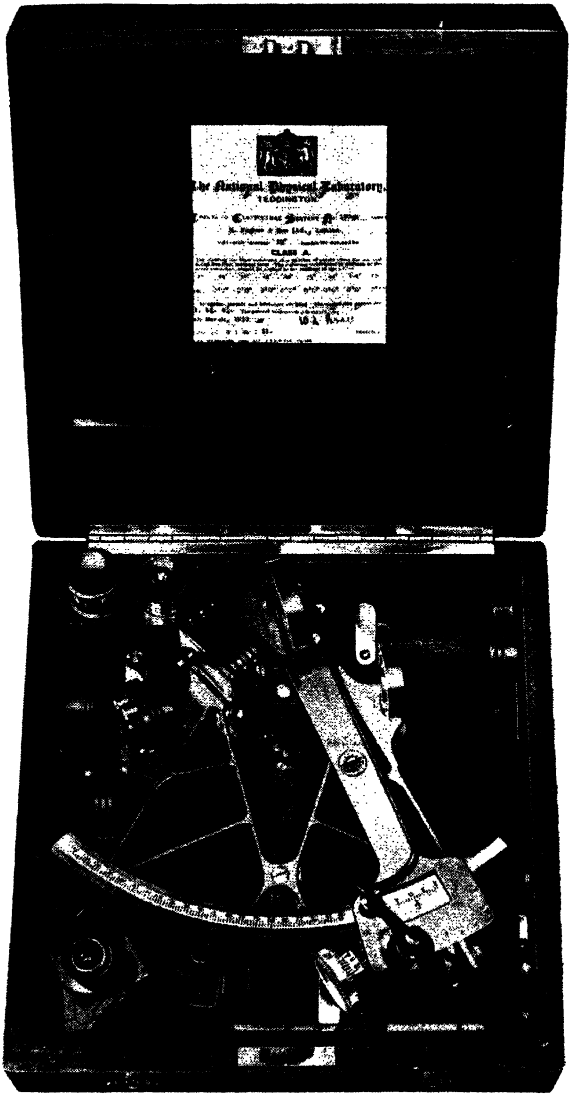


Fig. 9.—SEXTANT IN CASE.

Great care is taken to ensure the back of the limb being perfectly in contact all over the surface plate and it is finally clamped down at three or four points. The vernier is treated in the same way and the length is very carefully laid off from the arc of the sextant.

The method of dividing recommended by the Commissioners of Longitude in 1767 contains the principle upon which the dividing engines are constructed. It can briefly be described as setting off a radius which is a measure of a chord of 60° on the circle to be divided, and by bisection and subdivision filling up the space between the principal points. Another method of dividing, known as stepping, is sometimes employed. In this a chord of a number of degrees, say 16°, is taken from the measured radius, laid off a number of times in succession, and filled in by bisection.

The arc of a sextant is usually graduated to divisions of 10 minutes each, as the number of parts into which the section of the dividing circle requires to be subdivided is very great. To obtain this both methods are employed to ensure practically perfect results.

Errors of graduation in a sextant may be described as of two kinds, regular or accidental. The regular errors arise from a want of coincidence between the centre of the vernier and the centre of the graduated arc. These errors, which recur at regular intervals according to a periodic law, are not caused by defective dividing, but by defects in the fitting of centre or socket, however slight, or by want of perfect flatness in the limb.

Accidental errors, which follow no regular law, may occur at any given division, due to a peculiar strain in the limb or contraction of the sextant at that point.

The errors of graduation or eccentricity of a sextant can only be found by comparing the various angles measured with the sextant with their known values found by some other means. This is carried out by the National Physical Laboratory at Teddington, where there has been lately erected a new system of collimators

fixed at various positions round a centred pillar, with illuminated wires to take the place of stars.

The equality of the distances throughout the arc may be tested by successively placing the index of the vernier in exact coincidence with each division of the limb until the last division of the vernier reaches the last division of the limb. The arc usually extends from 0° to 130° or 140°, and figured at every 10°; each degree is marked by an outstanding line. In all the best instruments the arc is extended 5° to the right of zero in order to provide excess divisions for obtaining the index error.

Dividing the Micrometer Sextant.—In the micrometer sextant where one tooth is the equivalent of one degree of altitude, the dividing on the limb is used merely to count the number of complete revolutions of the micrometer screw, *i.e.* the number of degrees. The accuracy of the dividing in this case has no effect on the accuracy of the measurements, but the instrument maker nevertheless divides this scale as accurately as he can for the sake of appearance.

The divided head mounted on the worm shaft which measures the partial rotation of the worm is divided into minutes and is actually part of the measuring mechanism, and is therefore divided accurately.

The Vernier, so called after its inventor, Pierre Vernier, a Frenchman who lived about 1630 (sometimes called a Nonius after the Portuguese, although the invention of the latter was different), consists of a small arc concentric with the circle, and graduated into a number of divisions which occupy the space of $n-1$ divisions of the circle.

Then if $d =$ value of a division of arc

$d' =$ value of a division of vernier

$$(n-1)\,d = nd'$$

$$d' = \frac{n-1}{n}\,d$$

$$d-d' = \frac{1}{n}\,d$$

$d-d'$ is called the least count of a vernier, which is, therefore $\frac{1}{n}d$ of the circle division.

The least count of the vernier in sextants for astronomical observations is usually 10″, but for surveying work it can be made 20″ or 30″.

If $d-d'=10''$ and the sextant arc is divided to 10 minutes, then $n=\frac{d}{d-d''}=\frac{10'}{10''}=$ 60 divisions $=10°$ and the length of the vernier $=59$ divisions $=9° 50'$.

In actual practice for clearer reading the vernier is extended by using every other division on the arc, and we get—

$$2n = 20''$$
$$2n-1=19° 50'$$

To read off observations on the vernier, note where the zero of the vernier is and read off the value of the nearest division of the arc to the right of it. Then run the eye along the vernier to the left until you find the vernier line which coincides with an arc graduation. This value can be read from the vernier and added to the first reading off the arc.

To read an angle on the arc of excess, read left to right the number of degrees and minutes on the arc between its zero and the zero mark of vernier. Read off the vernier as before and subtract from 10′, add the difference to the arc reading. If the vernier is figured both ways this reading can be had without subtraction.

CHAPTER IV.

THE BOOTH BUBBLE HORIZON.

THE marine sextant is normally used in conjunction with the visible horizon, which provides the datum from which the altitude of the heavenly body is measured. The marine navigator is prevented very frequently from obtaining satisfactory observations due to the fact that, whilst the body to be observed is plainly visible, impaired visibility does not allow the horizon to be seen distinctly enough to use it as a datum. Many devices were tried in order to produce some means of ensuring that the line of sight of the sextant was maintained truly horizontal whilst the observation was being made, and the Booth Bubble Horizon was finally produced.

If a sphere be filled with liquid and a small air bubble be introduced, the bubble will take up a position such that the direction of a straight line drawn from the centre of the sphere to the centre of the bubble when it is at rest will be truly vertical.

If a collimating lens be placed in the centre of the sphere, the light rays passing through the bubble will be projected vertically downwards as a parallel beam, and these rays can be used as a datum in the same way as those from the natural horizon.

In the Booth Bubble Horizon the datum line is given by the rays passing from the centre of the bubble to the centre of the collimating lens placed at the centre of curvature of the bubble surface, and this vertical datum line is reflected by a mirror or prism rearwards and upwards at an angle of 45° to the horizontal, and passes through an unsilvered index mirror which is rotated about a horizontal axis to obtain coincidence of the bubble image and the object whose altitude is required.

As explained in Chapter II, rotation of the index glass enables the angle between the object and the datum line of sight to be measured, and when, as in this case, the datum line of sight is vertical, the scale can be compensated to give the same reading as if the datum line of sight were horizontal. In the same way, a tilting of the instrument in the plane of measurement will not impair the coincidence between datum and object, provided the difference in the number of reflections is zero or an even number when the bubble is viewed from below, or is an odd number if the bubble is viewed from above.

In Fig. 10 *B* is the bubble; *C* is the collimating lens having its optical centre at the radius of the curvature of the surface controlling the bubble; *D* is the reflecting surface of a mirror or prism reflecting the rays upwards at an angle of 45° to the rear; *M* is an index mirror through which the rays pass to the eye. Rays from the distant object *S* are reflected from the mirror to the eye, and on their passage from the mirror to the eye coincide with those coming from the bubble system.

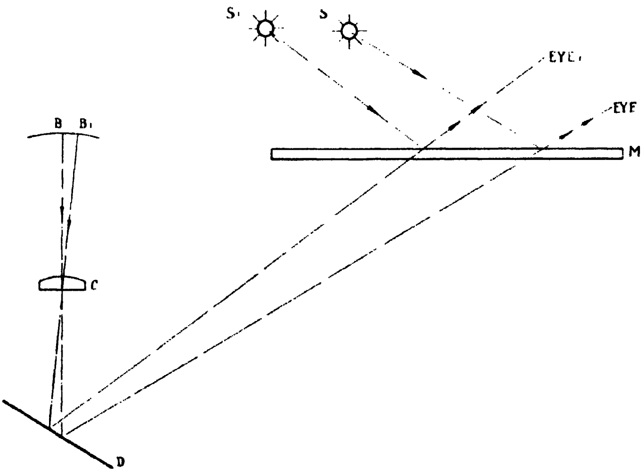


Fig. 10.

If the whole system is tilted forward and downward by a small amount, B will move to B', making a line through B' to the centre of the collimating lens C truly vertical as before, but the new vertical B' C will strike the reflecting surface D at a different angle by the amount of the tilt, so that the ray reflected upwards to the rear will have been changed in direction by twice the amount of the tilt; it will then pass through the index mirror M and to the observer's eye at Eye′. The index mirror M' which has been tilted with the instrument will reflect the object as before, but the reflected rays will differ in direction from the rays reflected before tilting by twice the angle of the tilt, so that they will again coincide with the rays from the bubble reflected from the mirror D and passing through the index mirror M; consequently the coincidence has not been impaired in any way by the small tilt.

If a reflecting mirror or prism is placed above the bubble in conjunction with a suitable collimating lens, the natural front horizon can be adjusted to coincide with the bubble, and a similar argument will show that the coincidence between front horizon and the reflection of the celestial object is also unaffected by small tilts if the correct number of reflections are employed.

The bubble chamber of the Booth Horizon is constructed with a top and bottom of accurately ground and polished glass, and the curvature of the top bubble lens is such that its radius is equal to the focal length of the optical system. This ensures that if the sextant is held slightly out of the vertical, either laterally or longitudinally, the bubble will still take up a position on the vertical line between the two mirrors; and as long as the reflected image and bubble remain in coincidence the observation should be accurate when the bubble is absolutely free from the sides of the chamber.

The bubble chamber is equipped with an air compensation which permits the adjustment of the size of the bubble, according to the body to be observed. This also automatically maintains the bubble at a constant size under varying atmospheric temperature

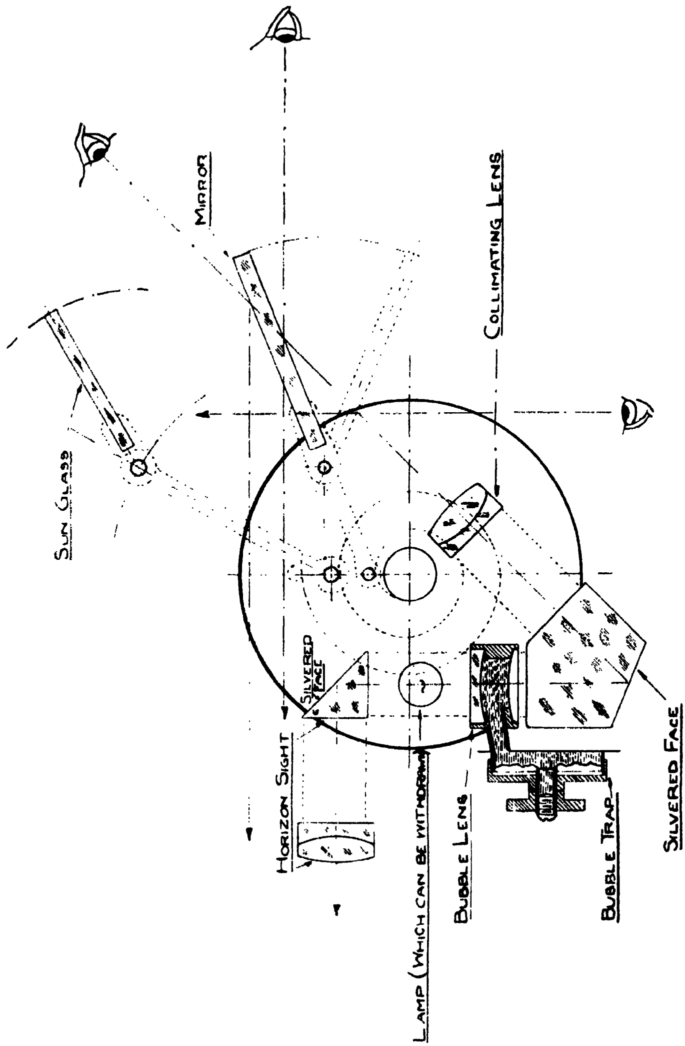


Fig. 11.—OUTLINE DIAGRAM OF BOOTH HORIZON.

changes. An adjusting screw with milled head is provided to alter the size of the bubble and experience will tell the observer the best size to use under different conditions. For solar observations, the bubble should be slightly larger than the image of the sun, whilst for star sights a slightly smaller bubble will be better.

The two lenses form a unit power telescope through which the true horizon can be viewed and used as the datum if it is desired. In daylight the bubble is illuminated by natural light, but at night a small electric bulb can be inserted into the horizontal sight tube for this purpose.

The bubble is sensitive to one minute of arc and on a steady platform observations to this degree of accuracy can be obtained. The motion on the deck of a ship will cause slight discrepancies and it is advisable to take a series of five or six observations and to use the mean of these in order to obtain satisfactory results. With constant practice and experience, great accuracy can be attained, and on occasions when the sea horizon is doubtful or obscured the bubble horizon is a great boon to the navigator.

The Booth Horizon is incorporated in a number of air sextants and observers have obtained excellent results from the use of these instruments.

It has also been adapted for attachment to the marine sextant, where it is placed in position on an extension in front of the horizon glass by means of a screw with milled head.

As described in Chapter II, when the bubble sextant is fitted to the marine sextant as an attachment it will be necessary to have an even number of reflections, because the rays from the observed object are reflected twice, viz. at the index and horizon mirrors. The optical construction of the Booth attachment is modified accordingly, and it then has the property of being insensitive to small rotations in the vertical plane. In consequence of this property the accuracy with which it is placed in position on the sextant has no effect on the datum line to which the observations are being referred, and any special precautions with regard to exact positioning of the bubble attachment are unnecessary.

CHAPTER V.

THE CONSTRUCTION OF AIR SEXTANTS.

These instruments are designed for use in aircraft for the observation of heavenly bodies for purposes of astronomical navigation. Due to the conditions under which they are used, certain modifications in structural design will be found when they are compared with the marine type.

A is a transparent mirror which is rotated in the vertical plane about its shorter axis by a lever and cam.

B is the horizon sight tube which admits a horizontal ray of light to the bubble chamber.

C is a graduated drum which is read against an index for the observed altitude. It is graduated in whole degrees and five minutes of arc and is used in conjunction with—

D a scale graduated in tens of degrees of arc.

E is a wooden grip by means of which the instrument is held in the left hand.

F is a milled ring by rotation of which the illumination of the bubble chamber can be regulated.

G is a wooden handle which is operated by the right hand to alter the position of the mirror and the reading of the scale drum.

H is a set of three shades for interposition between the sun's rays and the mirror.

K is a lamp for illuminating the scales at night, and operated by rotation into position over the scales.

L is a lamp for illuminating the bubble. In daytime it is partly withdrawn from the sight tube, and when required for use

AIR SEXTANT MARK VIII.

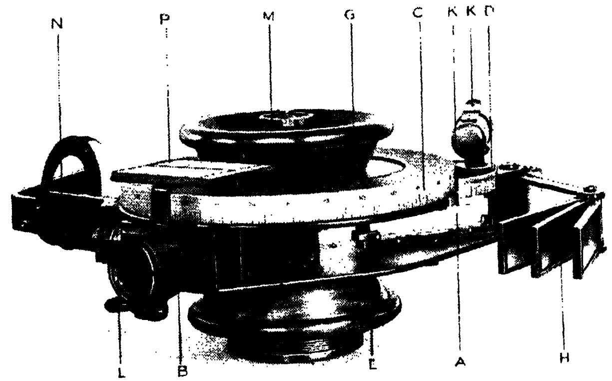


Fig. 12.

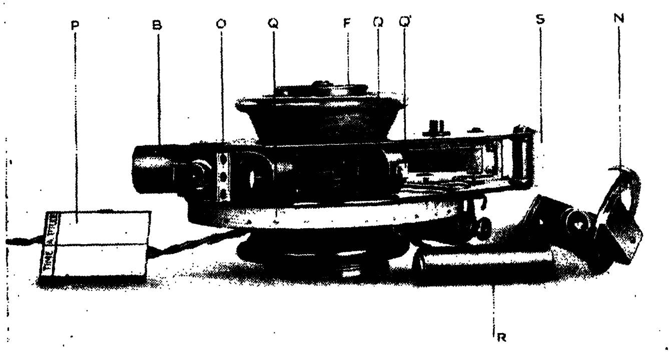


Fig. 13.

it is pushed home, the action of which completes the circuit and lights the lamp.

M is a milled head for producing a bubble and controlling its size.

N, *O*, *P*, *Q*, *R*, *S*, are respectively watch holder, fitting for same, notepad, spring clip for battery supplying currents for lamps, adapter for use with an accumulator instead of dry battery, and sponge rubber face guard. Most of these accessories are not provided with new instruments and they are found to be unnecessary.

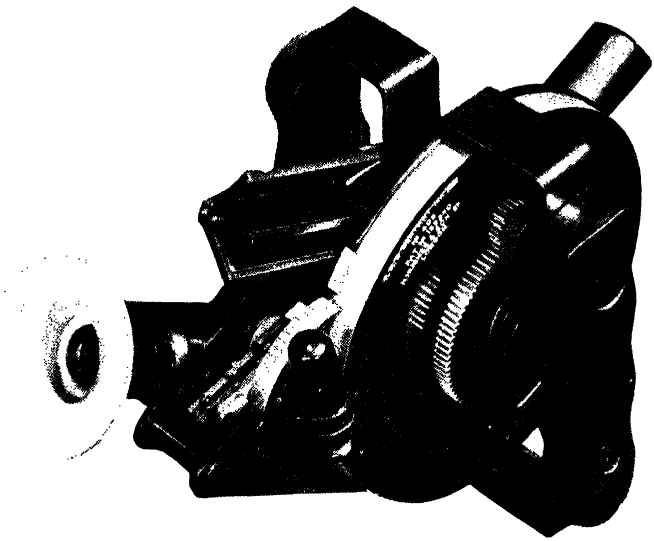


Fig. 14.—AIR SEXTANT MARK VIIIA.

This instrument is identical with the Mark VIII as regards the optical arrangements, except that a telescope is incorporated. The telescope is carried on an arm which can be moved to suit the requirements of the observer, and which can be turned out of use when not required.

The instrument is provided with two handles similar in shape to those fitted to the marine sextant, a marked improvement on

those of the Mark VIII. The movement of the graduated drum and mirror is carried out by means of a milled knob on a small gear wheel, which in turn drives a larger gear wheel fixed to the drum. This enables the movement of the mirror to be made to a much finer degree than before. The dry battery is replaced by a socket provided with a plug which is connected to a battery by means of a length of flex. Accessories such as notepad and watch-holder have been omitted.

Averaging Air Sextant.—As stated in Chapter V, when observing with the bubble sextant in the air or at sea, it is necessary to use the average of 5 or 6 observations. Hitherto the average of these has been obtained by the pilot forming the necessary arithmetical sum, dividing by the number of observations. In the sextant next to be described this is done mechanically.

In forming the average of a number of observations various modifications of the method may be employed. The usual way is to add the quantities together and divide by the number of observations; an alternative to this is to divide each observation by the number of observations and add the quotients, the result being the same whichever method is adopted. In the two methods just described, the whole of each observation has been drawn into the arithmetical work, although the variation between successive observations will probably be quite small. The amount of arithmetic can be considerably reduced by subtracting a constant quantity from each observation sufficiently large to bring the residue of each observation to a relatively small quantity, and providing the constant quantity is again added at the end of the arithmetical work the answer will be the same. It is of no consequence which of the two methods above-mentioned is used.

There are thus four methods of finding the average of, say, half a dozen sextant observations: (1) by forming the sum of the six observations and dividing by six; (2) dividing each observation by six and forming the sum of the quotients; (3) subtracting a constant

quantity from each observation forming the average by summing and dividing, and finally, adding on the constant quantity subtracted; (4) subtracting a constant quantity, dividing by six, adding the quotients and finally adding on the constant quantity first

AIR SEXTANT MARK XII.

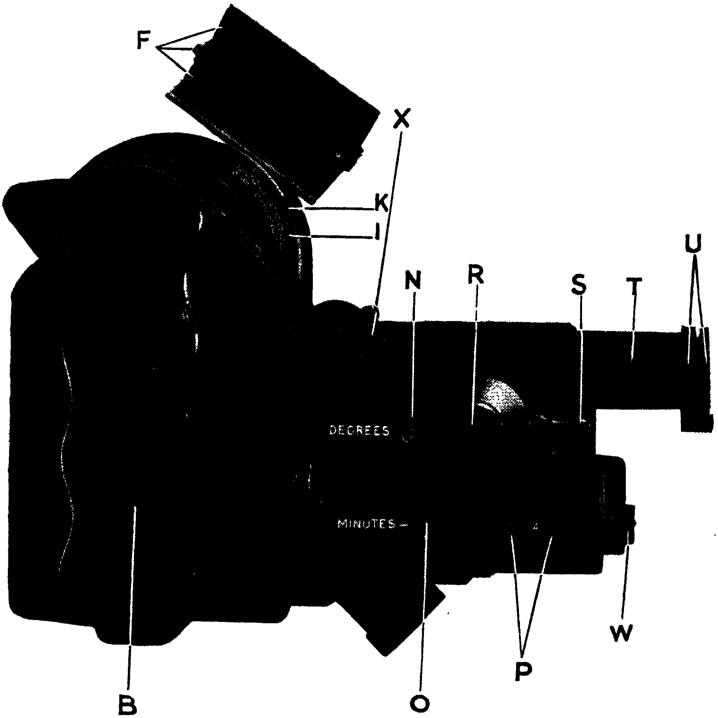


Fig. 15.

subtracted. The answers in all four cases will be the same. The last method has been adopted in the construction of the Mark XII air sextant now to be described.

The optical arrangements in this sextant are similar to those of the Mark VIII and Mark VIIIA already described, but the mechanical arrangements and manipulation are somewhat different.

The rotation of the mirror is carried out in two ways: (*a*) through steps corresponding to 10° differences of altitude, by rotation of a plate on a lever; and (*b*) by rotation of the lever about a transverse horizontal axis by means of a micrometer screw.

The first motion is obtained by mounting the mirror on a stainless steel plate which is provided, on the opposite side, with three

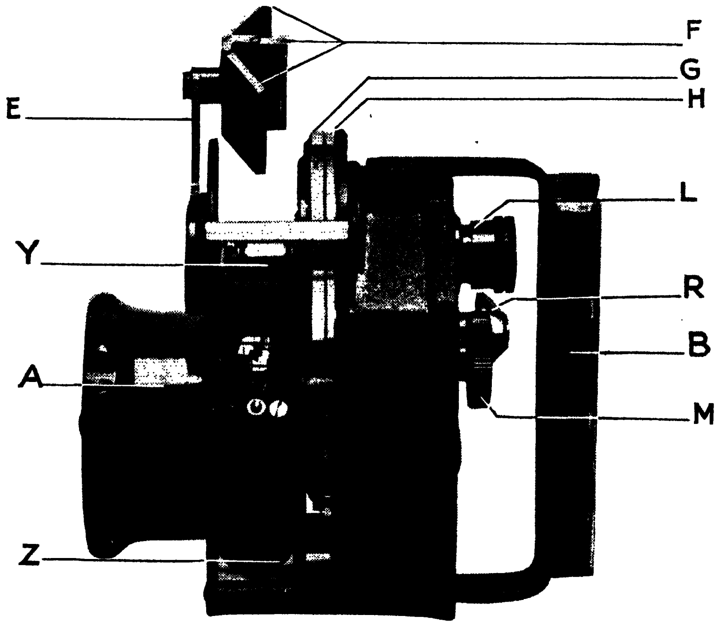


Fig. 16.

steel pins spaced 120° apart. A steel lever with an end of dimensions equal to that of the plate is drilled with three groups of holes on the same diameter as the circle defined by the three pins on the plate. These holes are 5° apart, and the groups are 120° apart. Pins and holes are very accurately placed and the plate and lever can be moved by steps of 5° relatively to each other, if the lever is disengaged and moved so that the pins engage in the next set of

holes. This results in a change of altitude of 10° as the mirror is moved.

The second motion is obtained from a micrometer screw pushing the lever against a spring. Provision is made for reading the corresponding changes of altitude in degrees and minutes on a suitable scale.

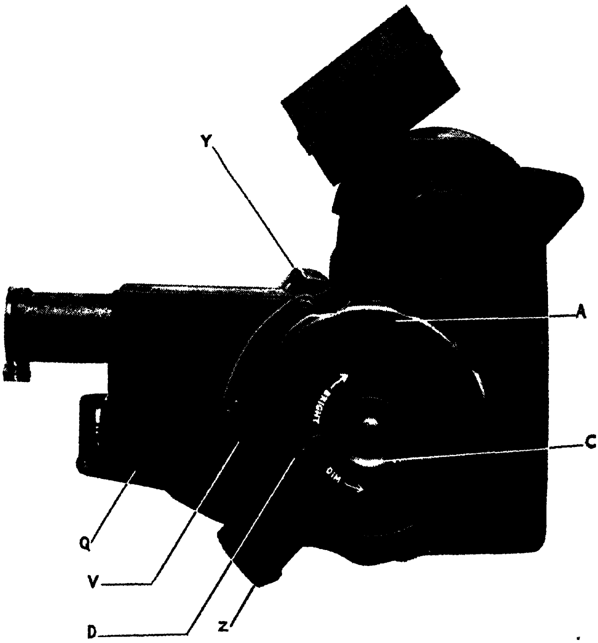


Fig. 17.

The three diagrams show the right and left sides and the rear of the instrument approximately in the position for observing.

The averaging of six successive altitude measurements is carried out mechanically by transferring one-sixth of the altitude measured by the micrometer screw to a totaliser as each coincidence is being made, declutching the totaliser and returning to the zero of the

micrometer screw before starting to make the next coincidence. Geared to the clutch mechanism is a shutter which cuts off the view of the bubble after the sixth coincidence has been made. The number of observations completed at any time is shown on the counter dial. The sextant is provided with engraved wheels showing the value of each single movement of the micrometer screw, which is utilised when taking single observations only. A second set of wheels shows the average of the micrometer screw observations when taking a series of six. The number of steps of 10° used as the fixed quantity for each series or for any individual observation is shown on a special scale, and being a multiple of ten only requires the tenth figure to be written in front of the value of the single observation or of the average of six, without performing any arithmetical work.

The three diagrams show the right and left sides and the rear of the instrument approximately in the position for observing.

A is the left handle.

B is the right handle.

C is the bubble control nut.

D is the rheostat and operating lever.

E is the shade arm.

F are three shades arranged to pivot as a group on the end of the shade arm; the centre shade is fixed to the pivot, whilst the two outer ones can be moved to adjust the intensity of shading as required. The shades can be moved out of the path of the rays entirely if desired.

G is the mirror plate carrying the mirror in its mount and fitted with the three pins as stated above.

H is the lever plate in which the sets of holes are placed. It is rotated about a conical ground centre by a micrometer screw.

J is the scale graduated in tens of degrees to show the amount of mirror movement.

K is an index against which the graduations on scale *J* are read.

L is the knob used to change the relative positions of plates *G* and *H*; it is pushed in against a spring to free *G* from *H* by disengaging the pins from the holes, rotated into the required position and released to allow the appropriate pins and holes to re-engage. In order to do this, the observer makes a rough coincidence of object and bubble with knob pushed in, and allows the pins to engage the nearest set of holes which place the object apparently below the bubble.

M is the fine adjustment knob which drives the micrometer measuring screw. Normally, before making an observation, the micrometer is returned to zero; in order to make coincidence the knob *M* is turned first in a counter-clockwise direction, thus apparently raising the object which has been placed below the bubble by moving of knob *L*. The knob *M* is then moved in either direction to effect coincidence.

N is a scale which shows the number of degrees through which the mirror has been moved in excess of the movement made when the pins and holes were engaged.

O is a scale of minutes of altitude which works in conjunction with scale *N*. Thus, when the observation has been made the sum of scales *J*, *N* and *O* gives the observed altitude.

P is a scale which shows the value produced by the totaliser, when a series of six "sights" is being made of which the mean is required.

Q is the lamp for illumination of the bubble, and is controlled by the rheostat *D*.

R is the lamp for reading the scales.

S is the switch for controlling the electric circuits; in its various positions it cuts off the current, switches on bubble lamp or switches on scale lamp.

T is the horizon sight tube.

U are two shades, one of plain frosted glass, the other of dark glass for use as required.

V is the clutch lever by means of which the totaliser is disconnected from the micrometer screw.

W is the totaliser clearing knob by means of which the totaliser reading can be set to zero.

X is a counter which indicates the number of observations made in a series.

Y is a screen which covers the bubble collimating lens when a series of six observations has been made.

Z is the battery container.

CHAPTER VI.

SEXTANT TELESCOPES.

TELESCOPES are divided into two main classes, astronomical and galilean. The astronomical telescope consists primarily of two lenses of the type usually known as positive; a positive lens is one which will form a real image in the same way as a burning glass or camera lens. The astronomical telescope is formed by placing two of these lenses at a distance apart equal to the sum of their focal lengths, and when a distant object is viewed through it the image is seen to be inverted. This type of telescope when used in conjunction with a sextant is known as the inverting or collimating telescope. It is a collimating telescope because crosswires can be placed to coincide with the image seen, and the wires can be adjusted so that absolute coincidence takes place and no motion of the head will then cause motion between the image and the crosswires, which are then said to be collimated to each other.

The second main class of telescope, the galilean telescope, has a positive front lens as before in combination with a negative eye-lens, the separation being equal to the difference of their focal lengths. The image seen through a galilean telescope is erect and no cross-wires can be arranged to coincide with it. When used on sextants, this telescope is generally called the erect telescope or star telescope, although its proper use is not for the observation of stars.

A third class of telescope known as erect collimating is really a modification of the astronomical telescope by the addition of an erecting system which may either be formed of lenses or prisms; apart from the fact that the image is erect its properties are the same as those in astronomical telescopes. In the actual telescopes,

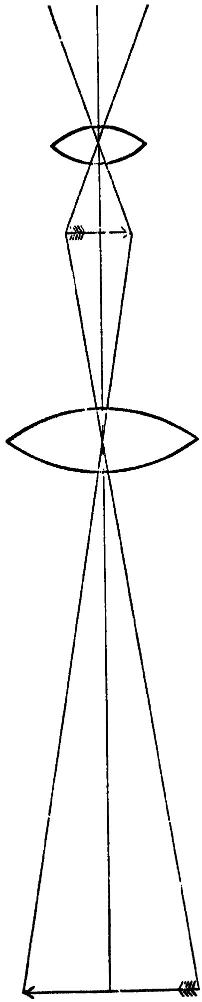


Fig. 18.—SIMPLE ASTRONOMICAL TELESCOPE.

most of the simple lenses that have just been mentioned are replaced by combinations of lenses in order to obtain better quality images. The front lens, or the system replacing it, is called the object glass, and the eye-lens is usually called the eye-piece.

Object Glass.—All the parallel rays from an object which fall upon a simple spherical lens cannot be brought to a single point focus in any case, but appear ill-defined and disfigured by coloured light. These defects are called spherical and chromatic aberrations. To render the telescope both aplanatic and achromatic, compound lenses are used in which the component lenses are made of glass of different degrees of refractive and dispersive power. One is a bi-convex lens of crown glass and is that which is turned towards the object; the other is a meniscus or concave convex lens of flint glass. By giving the four spherical surfaces of the component lenses suitable curvatures, both the spherical and the chromatic aberration produced by the crown glass lens are very nearly corrected by the flint glass lens.

Eye-pieces.—The eye-pieces most commonly used are of two kinds, the Huygenian and Ramsden. The Huygenian eye-piece consists of two plano-convex lenses of crown glass, the convex surfaces of both being turned towards the object. The first lens receives the converging rays, coming from the object glass before

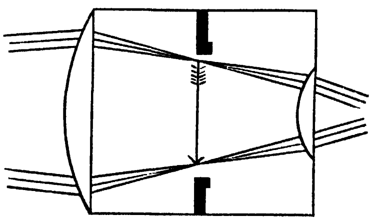


Fig. 19.—HUYGENIAN EYE-PIECE.

they reach the principal focus, and brings them to a focus halfway between the two lenses. The image formed at the focus of the second lens is distinctly visible to the eye behind it.

The Ramsden eye-piece consists of two plano-convex lenses, but the plane surface of the lens nearest the object is turned towards the object. The diverging rays from the image formed at the principal focus by the object glass are rendered less divergent by the first lens and parallel by the second lens. This eye-piece is used where spider threads are placed at the focus of the object glass for the purpose of measurements. Threads are, however, often placed in the focus of a Huygenian eye-piece merely to mark the centre of the field, as in the eye-piece of the telescopes of a sextant. Neither of these eye-pieces change the apparent position of the image which remains inverted.

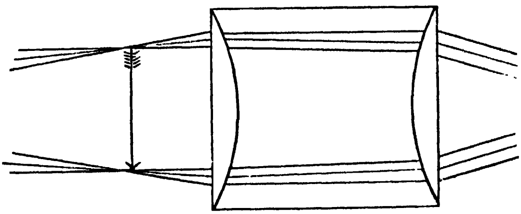


Fig. 20.—RAMSDEN EYE-PIECE.

In recent years a modified form of Ramsden eye-piece has been used in conjunction with an object glass of larger relative aperture in order to obtain brighter images. This type of eye-piece, known as a Kellner, is a Ramsden eye-piece in which the eye-lens has been replaced by an achromatic pair. When constructed of suitable types of glass, this eye-piece gives a flatter image, better definition and greater freedom from colour.

Achromatic eye-pieces designed to show objects in their erect positions usually consist of four lenses. They are chiefly used for land objects, as the great loss of light from the additional lenses is an objection to them for sextant purposes.

The lenses composing the eye-piece are fixed at the proper distance from each other in a separate tube, which has a sliding motion in

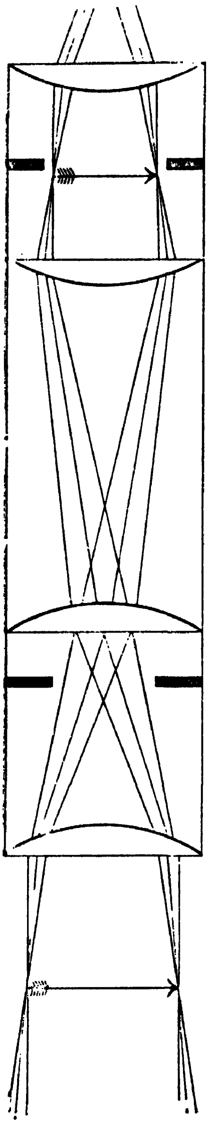


Fig. 21.—RE-INVERTING EYE-PIECE.

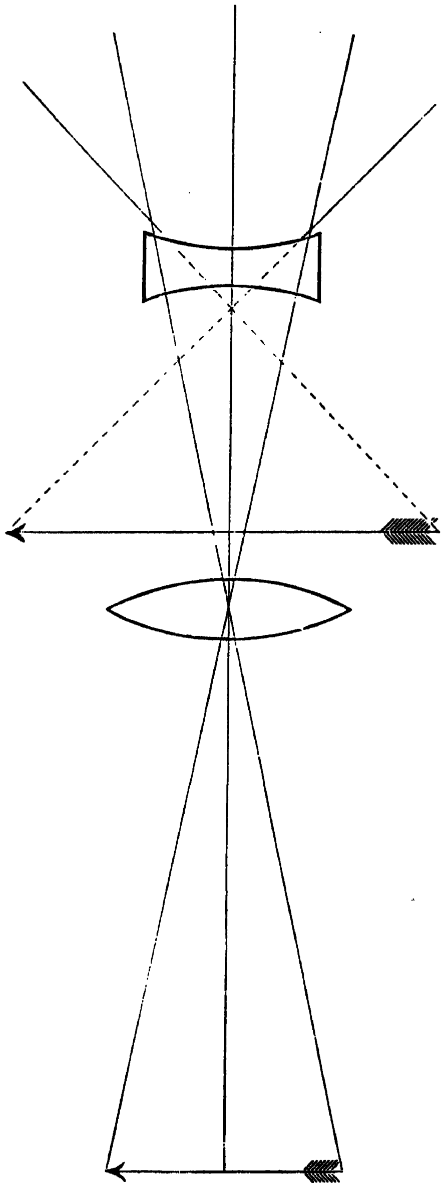


Fig. 22.—GALILEAN TELESCOPE.

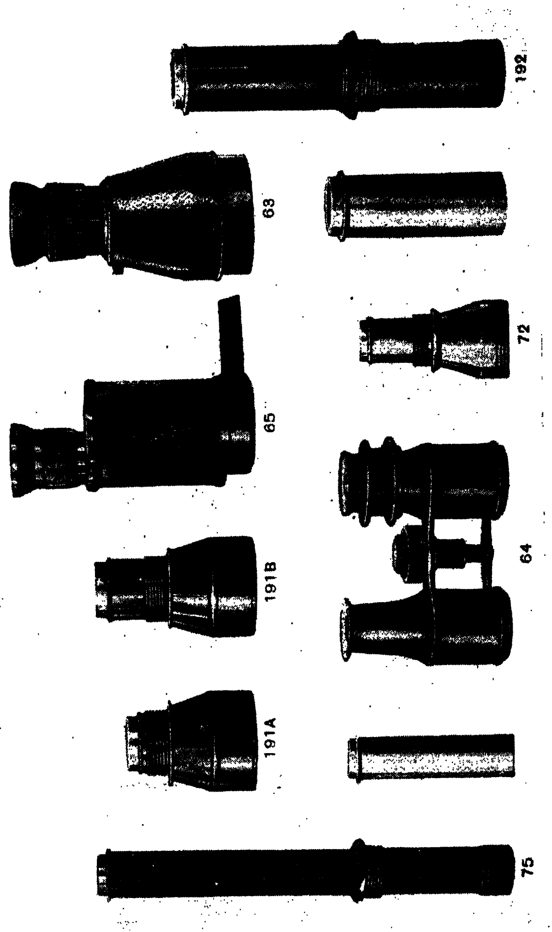


Fig. 23.

another tube, so that it can be pushed in or drawn out and thus adapted for different eyes.

The eye-pieces or powers of the inverting telescope used in a sextant are usually 5 and 10 diameters and in the erect or star telescope 2, 3, and 4 diameters. These provide a range of powers suitable and sufficient for all changes of weather and object.

In all star telescopes the object glass should be as large as possible and the larger it is the greater need of a suitable combination of lenses to render the telescope both aplanatic and achromatic.

Binocular glasses are sometimes fitted to sextants and are very convenient for observing stars, but great care must be taken in fitting them in the collar as they are very liable to give errors of collimation.

BRIGHTNESS OF IMAGES SEEN BY MEANS OF TELESCOPES.

When an object is seen through a telescope, the brightness of the image is found to vary according to the conditions and the telescope employed. This subject is of great importance to sextant users, as the accuracy of the angles measured must depend to some extent on the ability of the observer to see the objects defining the angle clearly and comfortably.

In any telescope there are two areas where all rays traversing the telescope must pass, and these are known as the pupils of the telescopic system. The object glass is one of these areas and is called the entrance pupil, because all rays entering the telescope must pass through it: the image of the object glass formed by the eye-piece must also have the same property, and it is called the exit pupil. Telescopes differ according to the nature and position of the exit pupil; for example, the sextant collimating telescope with wires in the eye-piece has an eye-piece which produces a real image of the object glass outside the eye-piece between it and the observer's eye. When the telescope is held about a foot away from

the eye and pointed towards a window, this image can easily be seen as a bright circular area near the outermost lens of the eye-piece and will move with the telescope. A little movement enables the observer to locate the position of the image quite easily: the reality of its existence and its position can easily be demonstrated by catching it on a piece of finely ground glass, or even thin paper, on which it can be focussed in exactly the same way as the image in a photographic camera.

When the same experiment is tried with the non-collimating type of sextant telescope, which is easily recognised by its conical body, the bright circular image of the object glass is seen to lie within the telescope itself where it cannot be caught on a ground glass screen or piece of paper. Even if the lenses are taken out of their mounts and held in position by any suitable means, the image cannot be caught on a screen because the exit pupil is a virtual and not a real image. The explanation of this may be found in optical text books.

This difference between the two types of telescope, one having a real exit pupil external to the telescope and the other having a virtual exit pupil inside the telescope, affects the brightness of the image seen through it. In the first type with a real external exit pupil, the pupil of the eye can be placed so as to coincide with it, when, if the eye pupil is large enough, it will receive all the light entering the object glass. In the second type, in sextant practice, the pupil of the eye is smaller than the virtual exit pupil of the telescope, and will be filled by rays whose direction is very close to the optical axis of the telescope. As the eye wanders from the centre of the field of view towards the margin, the rays, after a time, will no longer fill the pupil of the eye, and ultimately will not even fill any part; the effect is a central field of uniform brightness surrounded by a zone of gradually decreasing brightness, which also gradually fades to absolute darkness. In actual practice the optician keeps the central field and part of the zone of decreasing brightness

only, cutting off the outer part of the zone of decreasing brightness.

This zone effect is not present in the collimating telescope, where all parts of the field of view are equally bright.

The intrinsic brightness of the whole field of view of the collimating telescope and the central region of the field of view of the non-collimating telescope of the same magnification is the same when the losses by reflection at the lens surfaces are neglected. The actual value of the magnification has a great effect on the brightness of the image of a telescope; it will be sufficient to examine the case of the collimating telescope and to remember that the central region of the field of the non-collimating telescope will be the same. Optical text books show that, when the telescope is focussed on a distant object, the ratio of the diameter of the entrance and exit pupils is equal to the magnification. Consider first that the telescope is amply large for its purpose and that the exit pupil of the telescope which coincides with the pupil of the eye completely fills the latter. Consider, also, that the telescope is used to look at an area such as the expanses of sea and sky which are divided by the horizon. Let the magnification be M. An area of, say 1° of the sky will now be magnified M diameters and the light admitted by the object glass as entrance pupil will be spread over M^2 as much surface; the part of the exit pupil of the telescope utilised by the pupil of the eye will be supplied by a corresponding part of the entrance pupil which has a diameter M times as large as the pupil of the eye and admits M^2 as much light; thus, although the telescope has spread the light over an area M^2 as large, it has picked up M^2 as much light as the unaided pupil of the eye would have done, and the magnified image will be just as bright although so much larger. A small loss of light due to absorption and reflection losses is inevitable and has not been taken into account.

As the magnification increases, more and more of the available entrance pupil (object glass) is utilised until at last the exit pupil of

the telescope is the same size as the pupil of the observer's eye, which occurs when the magnification is the ratio of the diameter of the object glass (entrance pupil) to the diameter of the pupil of the eye. When the magnification is increased still further, the entrance pupil of the telescope cannot become any larger, and there is a reduction in the diameter of the exit pupil to something less than that of the pupil of the eye, which gives the unaided eye an advantage in the brightness of the image seen. This illustrates one of the advantages of the modern sextant telescopes, such as the Lumex series, over the older types; because, owing to their larger diameter, the magnification can be obtained without loss of brightness of the image.

The above considerations of brightness of image apply to objects having appreciable area: they do not apply to stars which do not appear any larger when seen through a telescope. In the case of stars, the larger the entrance pupil the greater the amount of light grasped and concentrated in the point image, provided it all enters the pupil of the eye. The entrance pupil is limited by the diameter of the object glass, so that, for a given diameter of object glass, it will be necessary to use as much magnification as is required to reduce the exit pupil of the telescope down to as small as or less than the pupil of the eye.

From these considerations it is easy to derive the following working rules:

To observe a star late at dawn or early at dusk, use as large a magnification as possible, because this will enhance the brightness of the point image of the star and reduce the brightness of the areas of sky and sea defining the horizon.

To observe a star early at dawn or late at dusk, use a low magnification to obtain maximum (natural) brightness of the sea and sky defining the horizon and to avoid undue concentration of light in the point image of the star.

The Lumex series of sextant telescopes have been specially designed to take the maximum advantage of these rules.

CHAPTER VII.

THE USE OF MARINE AND AIR SEXTANTS.

THE Marine Sextant, whilst primarily for use in observing the altitude of heavenly bodies, is readily adapted for use in measuring angles in any direction, when the angle to be observed is within the limits of the instrument.

When making an observation of the sun the instrument is held by the handle with the right hand, so that the plane of the instrument is in the vertical plane passing through the sun, whilst the axis of the telescope is directed at the visible horizon. The index bar is then moved along the arc, thus causing the index glass to rotate about its axis until the image of the sun and true horizon are roughly coincident. This movement is made by releasing the tangent screw from the teeth on the arc by means of the quick release, and when rough coincidence has been made the screw is allowed to re-engage. The fine adjustment of coincidence is made by means of the milled headed knob of the tangent screw, and the required limb of the sun is then brought into exact contact with the visible horizon. The angle is read in whole degrees by the arc graduations and the minutes are read from the micrometer scale fixed to the milled knob. Shades are nearly always necessary to reduce the intensity of the rays of the sun, and under certain conditions the horizon may also have to be shaded.

When a star or planet is to be observed, a slight alteration in the method of obtaining the rough coincidence is generally necessary. The index bar is set at zero reading and the axis of the telescope is directed at the heavenly body. It will now be seen direct through the unsilvered portion of the horizon glass, coincident with its

reflected image in the silvered portion. Maintaining the latter in view in the horizon glass, the limb of the instrument is slowly rotated about its centre until the horizon appears in view in the unsilvered portion, the quick release being again used in making the movement. As before, the final adjustment is made by means of the milled knob.

In order to bring the horizon to the star when sighting the star directly as just described, it is necessary to hold the sextant inverted, *i.e.* with the limb above the index mirror and centre.

During the day it may be necessary to adopt the same method to "bring down" the moon as was adopted for stars, but at night the moon is usually bright enough to handle in the same manner as the sun.

If the approximate altitude of any body is ascertained by calculation or from tables, this is set on the sextant, and when the horizon is seen through the telescope the required body should be within the field of view. When observing planets by day, it is invariably necessary to adopt this procedure, and, indeed, time is saved if all stars are handled in the same way.

Now that chronometers and time signals have rendered obsolete the lunar distance method of determining longitude, the sextant is no longer used for this purpose.

For the measurement of angles between terrestrial bodies, the procedure is similar to that for angles between two heavenly bodies. It is usually more convenient to hold the instrument "handle down" than "handle up", so if the two bodies to be observed are of similar distinctness the right hand one is "brought down" to the left, as in the case of two heavenly bodies. If, however, the left hand body is much more distinct, a better observation may be made by holding the sextant "handle up" and bringing it down to the right hand body.

The measurement of vertical angles of terrestrial bodies is made in a manner similar to that adopted for altitude measurements.

In all cases, care must be taken to see that the instrument is held exactly in the correct plane; and to ensure that this is being done it is advisable to swing the sextant slightly, when it will be seen that the reflected image will appear to describe an arc, the arc just touching the datum line which is being used.

Great care should be taken to focus the telescope accurately, to use the shades which will give the most favourable view and to ensure that accurate coincidence is obtained, and if these points are carefully observed satisfactory observations will result.

The Gothic Sextant has been designed for use either as an ordinary marine type, using the visible horizon as the datum from which to measure the altitude of heavenly bodies, or by attaching an artificial horizon, for use when the horizon is not available. For normal use, the instructions for handling the marine type hold good. If the horizon is not available, the bubble attachment is secured in place on an extension of the limb just in front of the horizon glass. The Booth Artificial Horizon is used, and this has been described in a previous chapter. The bubble is produced in the chamber by slightly tilting the instrument as if sighting at an elevation, and the control screw is gently screwed in until a bubble is seen. When a suitable size has been made the instrument is shaken lightly, the bubble will then move clear of the side of the chamber and the control screw should be released. The bubble can be reduced or removed by tilting the instrument down, screwing up the control screw some little way after feeling resistance, and releasing the control screw gently until the bubble has been reduced to the size desired or has been removed; finally, tilt upwards and completely free the control screw. The bubble must always be removed after use. The prismatic telescope or the low-power inverting telescope are the best to use with the bubble horizon, as it will be found that with the star telescope the light from the bubble may be cut off entirely. The prismatic telescope provides an upright image, whilst a little care is necessary with the inverting

telescope, to ensure that the two beams of light from bubble and object are seen equally. To do this the sextant is held as if observing and moved away from the body to about the extent of an arm's length. On looking at, and not through, the eye-piece, a circle of light will be seen. This is the Ramsden circle or exit pupil of the telescope through which all rays of light leaving the telescope must pass. The circle will be seen to be divided by a vertical line, which is the edge of the silvered portion of the horizon glass, which divides the two beams of light from the bubble chamber and object to be observed. The position of the rising piece must be adjusted so that this dividing line divides the Ramsden circle into equal halves, and it is thus ensured that the eye, when placed against the eye-piece, will receive both beams. By night, the diameter of the Ramsden circle will approximate to that of the pupil of the observer's eye, and very little difficulty will be experienced in receiving both beams. But during daylight the pupil of the eye will be considerably less in diameter, and it may be necessary to move the eye slightly from side to side to obtain the position whence both beams can be seen. The instrument must be held truly vertical when observations are being made, or an error similar to that of collimation will arise. The position of the bubble up or down the centre line is not important, always provided that it is completely clear of the side of the chamber. The motion of the ship may cause the bubble to oscillate slightly, and if this is seen to be the case a series of not less than five observations should be made, the means of the altitudes and times for the series being used. After a little practice the observer will attain to a considerable degree of accuracy and confidence, and whilst it is not claimed that the results will be as accurate as those made by use of the visible horizon, the observer will derive great comfort from the knowledge that he is enabled to obtain observations at all times when a celestial body is visible, no matter what the state of the sea horizon may be. This sextant has a very complete specification, including double star prism and lenticular.

The Mark VIII Air Sextant is fitted with the Booth Bubble Horizon, and the control of the bubble in this instrument, as in all air sextants mentioned in this work, is similar to that described for the Gothic Sextant above. For sun observations the bubble is lighted naturally, the lamp bulb being withdrawn from the horizon sight tube. The instrument is held so that the sight tube is approximately horizontal, and the eye is moved into such a position that the bubble is seen through the transparent mirror, and the instrument is then moved until the bubble is in the centre of its run. By manipulation of the handle held in the right hand, the mirror is turned until the reflection of the sun is seen in the mirror in exact coincidence with the bubble. The size of bubble for such an observation will be slightly larger than the apparent size of the reflected sun, and the reading is made when sun and bubble are placed concentrically. A suitable shade should be used to reduce the amount of light from the sun.

When making observations of stars and planets, the sextant is held so that the celestial body is viewed by looking upwards through the mirror. The instrument is held in this position and the mirror is turned by means of the handle until the image of the bubble is seen reflected from the under side. The bubble should be slightly smaller than for the sun observation, and the reading is made when the star is exactly in the centre of the bubble. The illumination of the bubble can be adjusted to suit the requirements of the observation, by means of the knob operating the rheostat, and the success of the observation depends largely upon careful adjustment or relative strengths of beams from celestial body and bubble.

If conditions are favourable, the horizon can be used as the datum for measuring the altitude of the body. The bubble is removed from the chamber, and the horizon is sighted through the bubble chamber. The body is "brought down" to the horizon and coincidence is made as with the marine sextant.

With a little practice, it is possible to obtain good observations of

horizontal and vertical angles between terrestrial objects, but unless the conditions of light and visibility are favourable the absence of a fairly powerful telescope makes it very difficult to pick up the objects to be observed.

The Mark VIIIA Air Sextant is operated in the same manner as the Mark VIII, except as regards slight differences arising out of modifications in construction.

The Mark XII Air Sextant is held in the left hand whilst the right hand grasps the right handle and manipulates the controls as required. The bubble is formed and controlled as in the other air sextants, and two methods of making the observation are available, this is, by reflecting the sun or moon, or by viewing the stars or planets direct. The bubble is illuminated by switching on the switch and controlled by means of the rheostat. The bubble and its illumination having been adjusted, the fine adjustment knob is turned as far as it will go in a clockwise direction, thus setting the indications at *N* and *O* to zero. The totaliser is cleared by depressing the clutch lever *V* and rotating the clearing knob *W* in a clockwise direction; the clutch lever is then released. Finally, set the counter *X* to zero by pushing the upper part of the milled edge in a forward direction. The instrument is now ready for use. If it is desired to make a single observation, the instrument is held in the chosen observing position. Knob *L* is depressed by exercising pressure as convenient with the fingers of the right hand, the left hand being used to resist this. When the mirror plate pins are freed from the holes, rotate the knob until approximate coincidence is obtained between object and bubble, then rotate knob slightly in a clockwise direction till the nearest group of holes is engaged by the pins when the knob *L* is released. This will cause the object to appear to drop below the bubble, and if knob *M* is rotated in a counter-clockwise direction, the object will appear to move towards the bubble again. Coincidence should now be made accurately by rotating knob *M* in either direction as required. Scale *I* is read for tens of degrees,

scale *N* for single degrees and scale *O* for minutes, the sum of these being the observed altitude. The value shown on the totaliser scale is not read. If a series of six observations of one body is to be made, the instrument is prepared as before, and the procedure for a single observation is followed as far as making the accurate coincidence with the knob *M*. The clutch lever *V* is depressed and knob *M* is turned in a clockwise direction as far as it will go, when the clutch lever is released. This action returns the micrometer screw to zero, whilst the totaliser retains one-sixth of the first measured angle on its scale. Coincidence is again made by turning knob *M* quickly counter-clockwise and then carefully in the required direction. This motion is conveyed to the totaliser and one-sixth of the angle is added to that already on the totaliser scale. The clutch lever *V* is again depressed, knob *M* turned to zero, and the third observation is made. The complete cycle of operations is repeated until six observations have been made, when one-sixth of each measurement will have been transferred to the totaliser and summed. This value, in degrees and minutes, is prefixed by the tens of degrees read from scale *I*, and the result is the average of the six observations. It is not possible to take more than six observations inadvertently, if counter *X* has been set to zero before commencement of the series, as instructed. On attempting to make a seventh observation the observer finds the bubble obscured by the cut off *Y*.

In the case of the above-mentioned averaging sextant, unforeseen circumstances such as cloud movement may prevent the completion of the series of six observations. In this event, the value shown by the totaliser cannot be used before mathematical adjustment has been carried out. As was shown in a previous chapter, the totalising mechanism divides each angle measured by six and sums the results. Therefore, if the value shown after any number of observations is multiplied by six and divided by the number of observations made, the result will be the value to be added to the present angle in order to obtain the average altitude for the partly

completed series. Care must be taken to ensure that no movement of the totaliser driving mechanism is made whilst the instrument is being reset for the second and subsequent observations of a series; if such a movement is made, the final reading will not be the true mean of the series.

In all sextants fitted with the Booth Bubble Horizon, the bubble should be removed from the chamber after use, and the bubble control eased to take pressure off the air chamber.

If electric lighting is fitted, the current should be carefully disconnected after use to avoid discharging the battery supplying the current.

CHAPTER VIII.

ERRORS OF THE SEXTANT AND THEIR ADJUSTMENT.

THE working parts of the modern sextant, whether of marine or air type, may be classified under three headings, namely, mechanical, electrical and optical, and the success of the observer depends very largely upon the state of adjustment of these parts.

As regards the mechanical and electrical parts, little can be said in a general way except that the former should be kept clean, free from moisture and lightly coated with thin oil, and that all electrical parts should be kept in the good order and condition necessary for their individual jobs. Each make of instrument will have its own adjustments for these parts, and detailed instructions for these are provided with the instrument when sold.

The Marine Sextant.- The errors to which the optical parts are liable are as follows:--

(1) The index glass being not perpendicular to the plane of the instrument.

(2) The horizon glass being not perpendicular to the plane of the instrument.

(3) The horizon glass being not parallel to the index glass when the index bar is at zero.

(4) The axis of the telescope being not parallel to the plane of the instrument.

(5) Prismatic effects in shades and mirrors due to faults in attachment and manufacture.

(6) The centre of the arc being not coincident with the centre about which the index bar rotates.

(7) The arc graduations being inaccurately cut.

(1) This is known as the error of perpendicularity, and the ray of light from the observed body is not reflected to the horizon glass in a plane parallel to the plane of the instrument. This necessitates the slight tilting of the instrument in order that coincidence with the horizon can be made and, as a result, the angle measured is not truly perpendicular to the horizon. To test for this error, the index is placed about the centre of the arc, and the instrument is held in a horizontal position with the arc away from the body. On looking obliquely into the index glass, the true and reflected images of the arc should appear in the same straight line. If adjustment is necessary, this is provided in the case of square mirrors by means of a small screw set on one edge of the back of the frame. When turned this presses against the back of the mirror, which is kept up to its job by a spring clip. In the case of circular mirrors, this means of adjustment is not provided, the base of the frame which holds the mirror being carefully filed to give perfect perpendicularity when the mirror is fitted.

(2) This is known as side error, and produces an error similar to that produced by (1). To test for this method at night, the index bar is clamped at zero and a distinct, but not too bright, star is observed. When the tangent screw is moved a little on and off the arc, the true and reflected images should coincide as they appear to pass. The sun, moon or any well-defined object can be used in the same manner during the day, or the instrument can be held in a horizontal position, the horizon viewed in the silvered portion of the horizon glass, when it should form a continuous straight line with the true horizon which will be seen to stretch away on either side. This latter method should not be employed if it is possible to use the former. Adjustment may be carried out by means of a screw set in the back of the mirror frame.

(3) This is known as index error and produces an error due to the fact that the reflected ray of light from the index glass is reflected a second time in a plane which is not parallel to the original

ray when the index is set at zero. It is not strictly necessary to adjust this error, as it is easily determined and allowed for when reading the angle observed. To test for this error, the index is set very accurately at zero and the horizon or well-defined terrestrial object is observed. True and reflected images should appear coincident. At night a distinct star of second or third magnitude can be used, but under no circumstances must a near object be used or an error due to parallax will arise. If it is desired to adjust any error found, a second screw on the back of the horizon is provided.

(4) This is known as the error of collimation and arises from the fact that the ray from the silvered portion of the horizon glass is not received in a vertical plane which is parallel to that from the horizon. To test for this, the telescope provided with cross wires is used, and this must be placed in such a position that two of the cross wires are parallel to the plane of the instrument. A star is observed through the telescope and the index bar is placed 3 or 4 degrees on either side of zero, thus separating true and reflected images so that one appears near the top of the telescopic field and the other near the bottom. By revolving the telescopic tube the two images are made to appear in contact with the same edge of the wires. The cross wires will then be parallel to the plane of the instrument. With the wires in this position, two selected objects are selected whose angular distance is between 100 and 120 degrees, and the reflected image of one and the true image of the other are brought into coincidence on the wire nearest the plane of the instrument. By changing the position of the sextant slightly, without moving the index bar, the coincident images should appear on the wire farthest from the plane of the instrument. If coincidence is not maintained, adjustment can be carried out by means of the screws in the telescope ring. If the images appear to separate, the screw farthest from the sextant is slackened and the screw on the opposite side is tightened; if the images appear to overlap, the operation is reversed. This error will always cause the observed

angles to be too large and may become serious when measuring large angles.

(5) Shade error is due to the fact that the two faces of the shade glass are not perfectly parallel. Each shade should be tested separately by making an observation without the shade, and then with the shade; coincidence should not be impaired. If a combination of shades is likely to be used, these should be tested in position. No means of adjustment is provided but the error may be ascertained by noting the reading without the shade and comparing it with the reading with the shade. The errors thus obtained should be noted for future use. A prismatic mirror will cause an error for which there is no adjustment provided, and Professor Chauvenet gives the following method of finding the error due to this cause:—

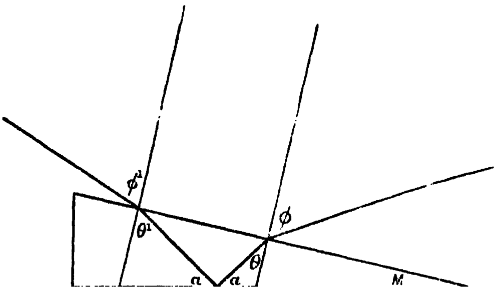


Fig. 24.

Let m=index of refraction for glass, then in Fig. 24

$$\left.\begin{array}{l}\sin.\ \phi = m \sin.\ \theta \\ \sin.\ \phi^1 = m \sin.\ \theta^1\end{array}\right\} \quad . \quad . \quad . \quad . \quad . \quad . \quad 1.$$

If we put M = the angle of prism, then

$$90^\circ - \theta = a + M$$
$$90^\circ - \theta^1 = a - M$$
$$\text{or} \quad \theta^1 - \theta = 2M \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad 2.$$

From the above, having ϕ, m, M given, we can determine ϕ^1 or $\phi^1 - \phi$. From Equation 1—

$$\cos.\ \tfrac{1}{2}\ (\phi + \phi^1) \sin.\ \tfrac{1}{2}\ (\phi^1 - \phi) = m \cos.\ \tfrac{1}{2}(\theta + \theta^1) \sin.\ \tfrac{1}{4}\ (\theta^1 - \theta),$$

whence by Equation 2—

$$\sin. \tfrac{1}{2}\,(\theta^1-\theta)=m \sin. M \, \frac{\cos. \frac{1}{2}\,(\theta+\theta^1)}{\cos. \frac{1}{2}\,(\theta+\theta^1)}$$

M being small it will be sufficient to take—

$$\sin. \tfrac{1}{2}\,(\theta^1-\theta)=m \sin. M \, \frac{\cos. \theta}{\cos. \theta}$$

or

$$\theta^1-\theta=2mM \sec. \theta \sqrt{1-\frac{\sin.^2 \theta}{m^2}}$$

which may be reduced to—

$$\theta^1-\theta=2M\sqrt{1+(m^2-1)\sec.^2 \theta}$$

put

$$q^2=m^2-1$$

$$\theta^1-\theta=M2\sqrt{1+q^2 \sec.^2 \theta} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad 3.$$

The error varies with θ, and consequently with the angle measured. Let r equal angle given by sextant. The whole error in the measured angle will be the difference of the errors produced at the reading r and at the zero point of the sextant; at the zero point let $\theta=B$. Hence the error will be the difference of the values of Equation 15, for $\theta=\frac{1}{2}r+B$ and $\theta=B$. If $r^1=$ true value of angle, then—

$$r-r^1=2M\left[\sqrt{1+q^2 \sec.^2 (\tfrac{1}{2}r+B)}-\sqrt{1+q^2 \sec.^2 B}\right] \quad . \quad . \quad 4.$$

m is 1.55 usually, $\therefore$ $q^2=1.4025$. If $M=10''$, $B=10^\circ$ and $r=120^\circ$, then $r-r^1=41''$.

The effect of the error is evidently less for small values of B than for large ones. Moreover, the smaller the angle B is, the larger the angle which can be measured by the sextant, for all reflection from the index glass ceases when $\theta=90^\circ$, and this value gives $r=180^\circ-2B$ as the limit of measures with sextant.

The preceding investigation is confined to the case where both faces of the index glass are perpendicular to the plane of the instrument, but this is the case in which the effect is greatest. The glass reflects from its outer surface as well as from the silvered face. If the faces are parallel, the images reflected from the two surfaces will converge to the same focus in the telescope and produce but a single image of the object. If the glass is prismatic there will be

two images; if the object is a star it will appear large or elongated. The best position of the glass, to examine this defect, is when the index is at the 120° end of the arc. If the instrument is found defective in this respect, determine the error as follows:—Adjust the instrument, determine the index correction and observe a large angle between two well-defined terrestrial objects. Now take out the index glass, turn it end for end, replace it, re-adjust the instrument, determine a new index correction; observe the same angle as before. Half the difference of the two observations, each having been corrected for its index error, is the error caused by the prismatic form of the index glass. Repeating the operation for various sized angles we can form a table from which, by interpolation, we can determine the error for any given angle. A prismatic form of horizon glass affects all angles the same, the index correction included, and therefore produces no error in the results.

(6) Centring error produces an error which varies at different parts of the arc and is due to an error in manufacture. No means of adjusting for this error is provided.

Mr. T. P. Baker gives the following excellent explanation of centring error:—

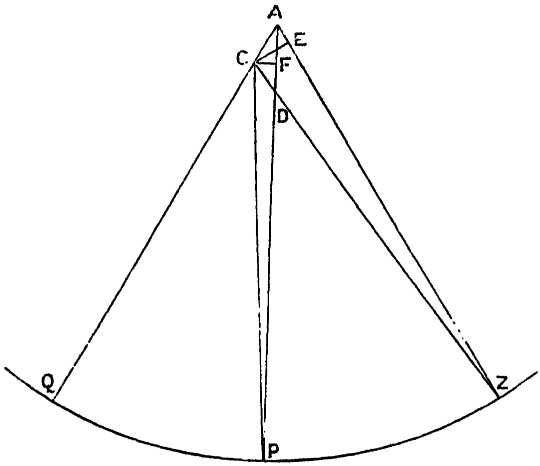


Fig. 25.

"Suppose A is the centre of arc and C the centre round which the arm rotates. P is the position of the vernier zero.

Then if Z is the zero the reading is $2\ P\ A\ Z$, but the angle rotated through by the arc is $P\ C\ Z$ and the true reading, being twice the rotation from zero of the moveable mirrors should be $2\ P\ C\ Z$. The reading is therefore too great by $2\ P\ C\ Z - 2\ P\ A\ Z$.

$$= 2\ \{ (P\ D\ Z - C\ P\ D) - (P\ D\ Z - C\ Z\ A) \}$$
$$= 2\ (C\ Z\ A - C\ P\ A)$$

Now since $\sin.\ C\ Z\ A = \frac{C\ A}{C\ Z} \sin.\ C\ A\ Z$

and $\sin.\ C\ P\ A = \frac{C\ A}{C\ P} \sin.\ C\ A\ P$

so that $2\ (C\ Z\ A - C\ P\ A) = \frac{2\ C\ A}{C\ P} (\sin.\ C\ A\ Z - \sin.\ C\ P\ A)$

since $C\ P$ and $C\ Z$ are very nearly equal and $C\ Z\ A$ and $C\ P\ A$ are both small angles.

If the centre, C always remains the same point in all positions of the arm, then we can look upon the first part of this error, viz.:—

$2\ \frac{C\ A}{(C\ P)} \sin.\ C\ A\ Z$ as a permanent error which can be conveniently included in the index error, and we can then say that the centring error is proportional to the sine of the arc $P\ Q$.

This variable portion will therefore vary as a curve of sines along the arc, having zero value at the point Q and A maximum $2\ \frac{C\ A}{C\ P}$ at a point 90° away from Q or 180° if we speak of the difference of sextant readings, since these are cut on a scale of one-half. In a sextant of 7″ radius the maximum error would be as much as 10″ if $\frac{2}{7} C\ A = \sin.\ 10''$; that is to say, if $C\ A$ were about .0002 of an inch. At the same time it should be noticed that if the line $Q\ C\ A$ fell about the middle of the arc, the maximum error possible could only amount to $\frac{2}{7} C\ A \sin.\ 35°$, so that in such circumstances $C\ A$ could be as much as .003 inch in order that the centring error should never be greater than 10″.

Centring Error.—The eccentricity of the centre can be found for the various angles of the sextant by measuring the distances of well-known stars and comparing them with the apparent distances computed from their right ascensions and deductions.

Professor Chauvenet gives the following equations:—

Let Z = sextant reading.
X = the index correction supposed to be unknown.
Z^1 = the true value of measured angle.
e = eccentricity and E = constant for sextant and putting $N = Z^1 - Z$.
n = $x + 2e \cos. E \sin. \frac{1}{2} Z^1 + 2e \sin. E \cos. \frac{1}{2} Z$.

To find the three unknown quantities x.

$2e \cos. E$ and $2e \sin. E$, it is necessary to have three equations derived from three angles falling in different parts of the arc, for example, near 0°, 60° and 120°. The error being found for certain places on the arc, the correction for any angle may be obtained.

Index Error.—This may be determined by viewing the sea horizon by the sun or by a star.

(1) *By the Sea Horizon.*—Hold the sextant perpendicularly and using the telescope, bring the direct and reflected image of the horizon into exact continuation of each other. The reading on the arc is the index error, positive on the arc proper, negative on the arc of excess. The index error is applied with the contrary sign.

By the Sun.—Clamp the index at 30′ on the arc proper, fix the inverting telescope, hold the sextant horizontally, bring the right limb of the reflected sun into contact with the left limb of the real sun, observe the reading on the arc. Clamp the index on the arc of excess and repeat the operation, observe the reading on the arc of excess. The reading on the arc proper is marked + and the reading on the arc of excess —. Take the algebraic sum of the two readings and the result is the index error with its proper sign.

By a Star.—Bring into coincidence the direct and reflected

image of the star. The reading on the arc proper or the excess will be the index correction to be applied with the contrary sign.

Bubble Sextant.—The errors of the bubble sextant or air sextant are of the same nature as those of the marine sextant just described. Index error will, of course, be of the same nature as before, and so on.

There is one error peculiar to the bubble sextant which requires special mention. It has been shown that making the coincidence with the bubble displaced in the plane in which the measured angle lies produces no effect as in the case of the ordinary sextant. A displacement of the bubble sideways or at right angles to this plane when making the coincidence involves making the measurement in a plane slightly inclined to the plane in which it is supposed to be made, with the consequence that the angle observed is larger than it would be if measured in the proper plane. This error is seen to be very similar to the collimation error of the marine sextant. It differs in one important respect—that it is not due to any defect in the instrument, but to the observer not holding the sextant correctly when observing.

In general, the errors of the bubble sextant do not receive such close attention as those of the marine sextant, because the accuracy aimed at is not so high. In the case of the marine sextant an accuracy of half a minute of arc in the angular measurement is demanded by the keen navigator, while with the bubble sextant the average of half a dozen observations in the air is liable to an uncertainty of about two minutes of arc or more, owing to the effect of casual accelerations on the bubble. It is for this reason that the errors of the bubble sextant are most frequently ignored, as in good instruments they are known to be below this value. The error due to sideway displacement of the bubble when observing may quite easily introduce errors in excess of this value, and in the case of high altitudes they may become quite large; it is therefore most important to guard against this error.

CHAPTER IX.

MODERN SEXTANT ACCESSORIES AND NAVIGATION INSTRUMENTS.

THE steady improvement in sextant design has been accompanied by efforts on the part of the scientist to produce appliances for use when making observations, which will render the results as perfect as possible. Under favourable conditions, the sextant in its present form should give all that can be desired of it, but the frequent recurrence of conditions which are not favourable necessitates the use of some auxiliary appliance which will wholly or partly overcome this. The marine navigator of the past had to depend upon the sun, moon and stars at dusk and dawn for his observations, and he was frequently deprived of the opportunity by poor visibility. The rapid improvement of the bubble artificial horizon has gone a long way towards making the observations less dependent upon good horizon conditions, and this has already been dealt with in previous chapters.

The Lenticular is a cylinder lens fitted between the index and horizon glasses to intercept the star and draw the image out into a line or band of light parallel to the horizon, thus ensuring that perfect coincidence is made. The index error of the lenticular, if any, can be found by making an observation of a star in the manner described in the chapter on sextant errors.

The Wollaston Prism is a pair of cylindrical prisms in the form of two wedges, with sufficient difference in thickness or refractive index to form two distinct images of the observed star. One is moved a little above the correct line and the other a little below, and

in conditions of hazy horizon, a much more accurate coincidence is made by observing the horizon between the two images. The prism is fitted between the index and horizon glasses.

The Double Star Prism is similar to the Wollaston prism but is less expensive.

The MacKenzie-Nicol Prism is designed to obviate the glare of the horizon when the sun's altitude is low. It acts as a polariser and is fitted in the inverting telescope on the object glass side of the diaphragm. It is so placed that, when the telescope is screwed home, the polarising plane of the prism is parallel to the plane of the instrument, and consequently perpendicular to the plane of the horizon when the sextant is in position for making observations.

The Sextant Stand is used for shore survey work only, as the accuracy of observations is greatly increased when the sextant is fixed so that it is held steady in any desired plane.

The stand consists of a vertical brass pillar, supported by a tripod standing on three adjustable screw legs, the points of which rest on the ground or table on which the stand is placed. The head of the stand consists of a cap fitted on the top of the pillar, carrying a stout cross bar with two brackets, in which the horizontal axis turns. Attached to each end of this axis are the counterpoise weights and in the middle of the axis is fitted the spindle which carries the sextant. In the improved forms, the counterpoise weights can be adjusted to any weight of sextant, and the horizontal axis is attached to a circular base plate which can be clamped and slow motion imported to it by a tangent screw.

The Quintant, Sounding Sextant and Double Sextant are instruments used for survey work.

The Quintant.—Instruments capable of measuring up to 144° are termed quintants. After 120° in an ordinary sextant the relation between the index and horizon glass becomes such as to render observations impracticable. By placing the telescope holder close

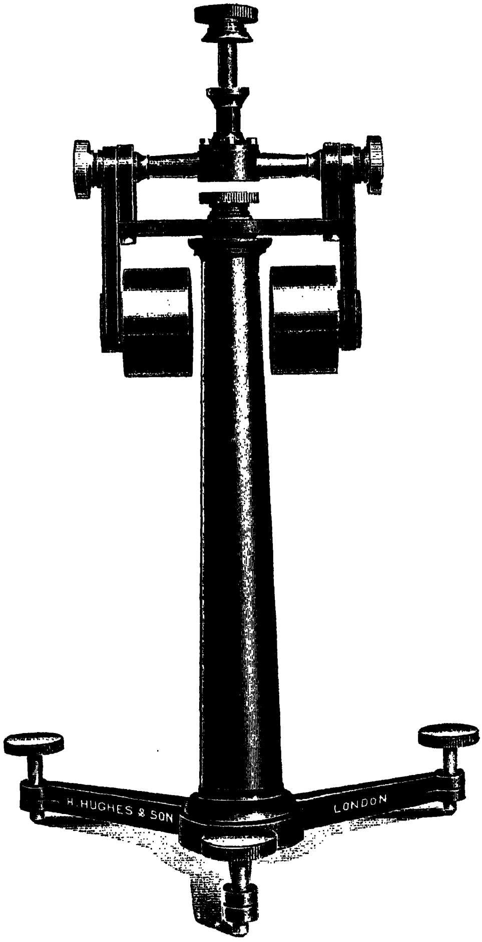


Fig. 26.—SEXTANT STAND.

up under the index mirror and shifting the horizon glass to the extreme end of the arc so as to make the angle formed by the centre line passing through both mirrors and that passing through the

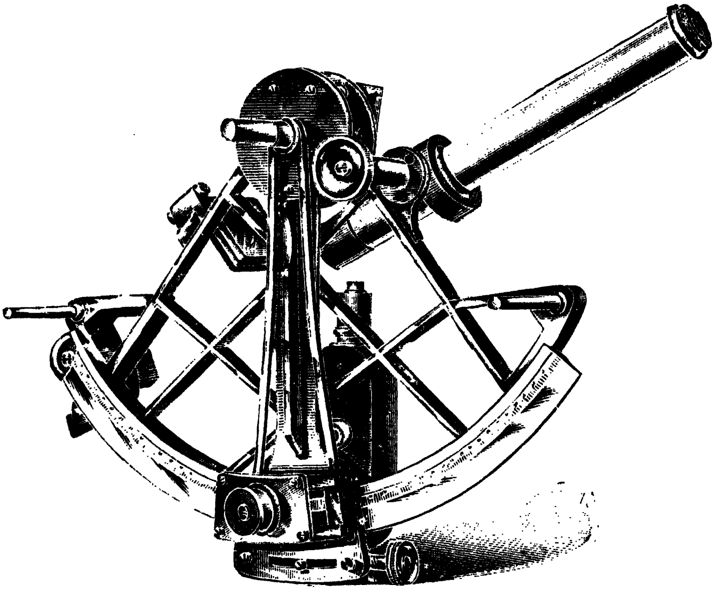


Fig. 27.—THE QUINTANT.

horizon glass and the axis of the telescope as acute as possible, the index bar is given a freer range and a larger angle can be measured.

The index and horizon glasses are very successfully fitted on the back of the instrument and the legs in front, that is on the side of the arc, this being a great convenience in setting down or taking up the instrument and also allowing of the magnifying arm being fitted at the same centre as the vernier. This instrument is specially adapted to artificial horizon work and measurements of large angles generally.

Sounding Sextant.—This is a special form of sextant for use in surveying. It chiefly differs from the observing sextant in being

generally lighter and handier; in having the arc cut only to minutes and in having a very large telescope.

The index and horizon glasses are made very large and the shade frames omitted. A shade head and blank head are supplied with the sextant.

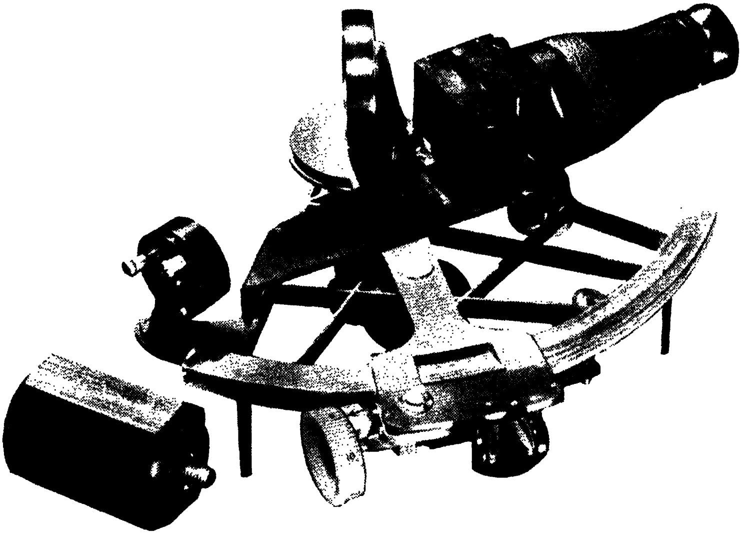


Fig. 28. SOUNDING SEXTANT.

The illustration shows a pentagonal prism fitted in front of the telescope to extend the range of angles capable of measurement by the survey sextant by a fixed amount of 90°.

The Double Sextant.—The Double Sextant was designed for taking three points and other shore bearings.

This instrument consists of a whole circle with a 5 or 6-inch arc, fitted with two indices, two index mirrors with one over the other in the middle of the circle. The horizon glass is placed on the edge of the circle and is silvered top and bottom with a clear cut in the middle to observe the central object. The indices are fitted with clamp and tangent screws and read to 10″. A handle is fitted in

the middle of the circle over the centre work. Captain Lecky has described this instrument in his *Wrinkles*.

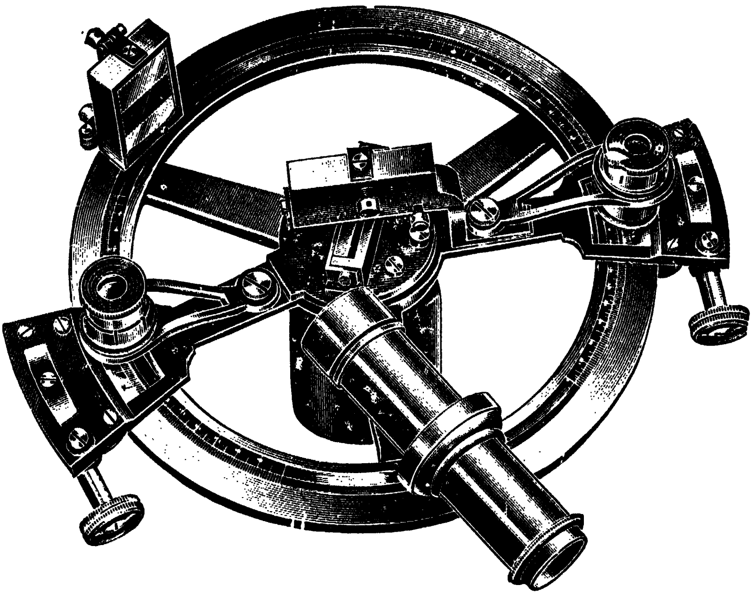


Fig. 29.—DOUBLE SEXTANT.

The double sextant can be used for harbour survey and river work and has proved a most valuable instrument in all work where speed, accuracy and portability are required.

Star Globe.—A Star Globe was introduced some years ago by Lieut. English, R.N. The globe is about 8 inches diameter, pivoted in a brass ring or meridian at the North and South Poles. The brass meridian is graduated from 0° at the celestial equator to 90° at either pole. The degrees on this meridian corresponding to the latitude must be brought directly under the zenith, or its complement on to the horizon. In north latitude the North Pole must be elevated, and in south latitude the South Pole.

On the equinoctial or celestial equator of the globe the hours of time are marked in Roman figures from the first point of Aries,

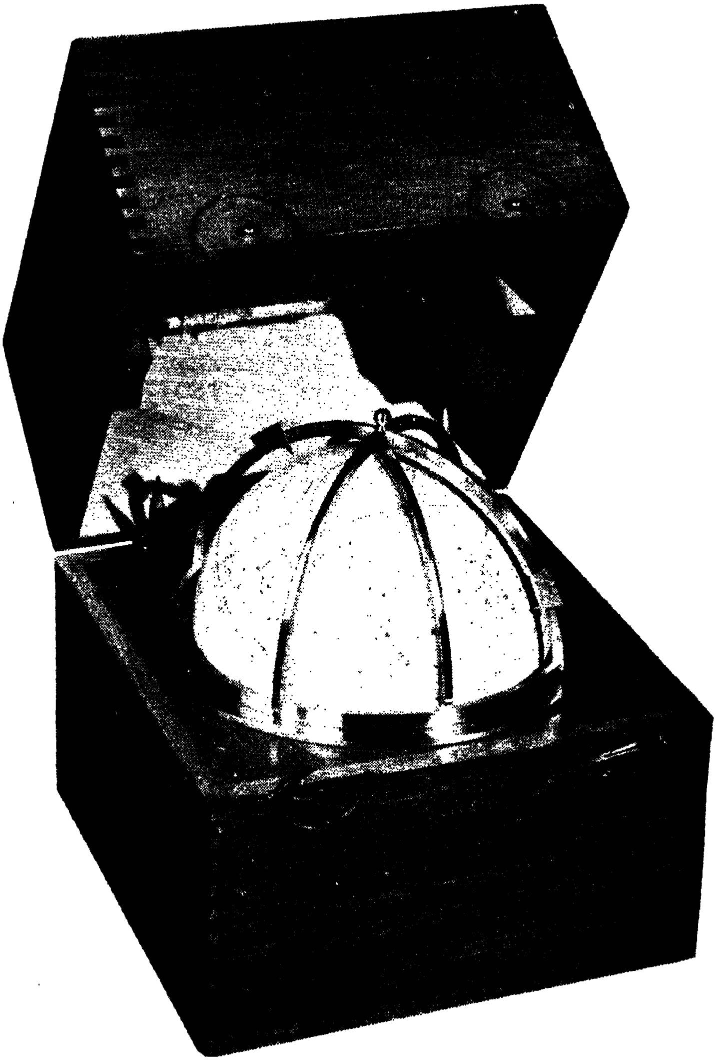


Fig. 30.—STAR GLOBE.

which is 0 hours to 24 hours, to the eastward right round the globe. To find the sidereal time at any desired moment the quantity R (equal to the right ascension of the mean sun ± 12 hours) tabulated in the *Nautical Almanac*, accelerated for the mean time at Greenwich (G.M.T.) at the time of observation, must be added to the mean time at the local place (L.M.T.).

Having thus found the sidereal time required, turn the globe round till this time on the equinoctial comes directly under the brass meridian. The instrument is now set for the time and latitude and every star is in its proper position above the horizon, and its altitude and true bearing can be measured by the graduated and vertical circles.

The Artificial Horizon is used for making observations on shore and for school work. It is a highly reflecting plain surface in a truly horizontal position. Mercury or any viscous liquid protected from the wind can be used.

The angle between an object and its reflection from the artificial horizon is double the altitude of the object from the observer's sensible horizon, therefore if the former be measured with the sextant and the reading halved, the result is the observed altitude of the object.

Suppose a ray from a star be reflected from the mercury of an artificial horizon to the eye, the direct rays from the star to the eye will fall in the direction of the dotted line. The small place between the eye and the mercury is insignificant in comparison with the distance of the star, therefore the rays falling on the eye and on the mercury respectively may be considered parallel. The reflected image of the star will appear to the observer in a continuation below the mercury of the straight line between the eye and the artificial horizon.

Now the angles of incidence and reflection A and B are equal, the opposite angles B and C are equal.

$\therefore A\ C = 2B = 2A$, and since the rays from the star to the mercury

and from the star to the eye are practically parallel, the angle $D=A+C=2A$.

The most reliable form of the artificial horizon is the shallow trough containing mercury covered by a roof in which are framed two carefully ground plates of glass whose planes are approximately

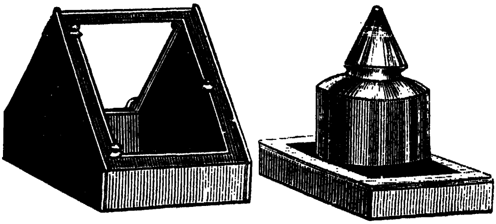


Fig. 31.

at right angles to each other and at an angle of about 45° to the surface of the mercury. The glasses should be parallel and marked with the certificate of the National Physical Laboratory. A bottle of mercury is supplied with this instrument.

A new form of horizon has been introduced into the Royal Navy, which consists of a shallow trough of metal gilt. This is amalgamated after getting the surface absolutely clean and free from grease, by wetting it with a few drops of dilute suphuric acid and then rubbing into it a drop of mercury until the whole surface is bright, when a very small quantity of mercury added will flow evenly and form a horizontal surface. The drop is wiped off with a broad camel-hair brush. A bubble is supplied with this form as the trough is mounted on three adjusting screws.

Captain George's horizon consists of a circular iron trough containing mercury on which a disc of glass with parallel faces floats. It is portable and convenient to use, but unless care be exercised when placing the glass on the mercury, and unless the latter be fairly pure and clean, rather large errors, quite unsuspected by the observer, may be introduced. Before floating the glass a piece of thin paper should be placed on the mercury, the

glass should then be put on and lightly pressed while the paper is carefully withdrawn.

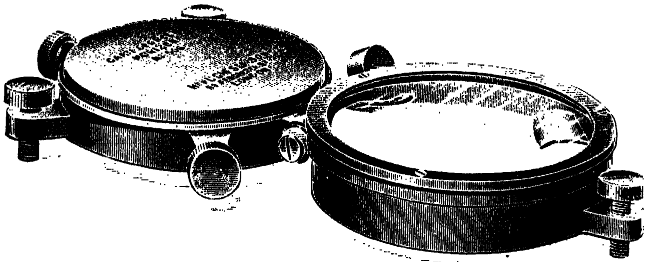


Fig. 32.

These horizons are fitted with a glass lid which screws on the top of the trough, and a circular cistern is attached into which the mercury runs when not in use. Three levelling screws are also fitted to the frame. The chief advantage of this horizon is that the whole surface of horizon is available for observation.

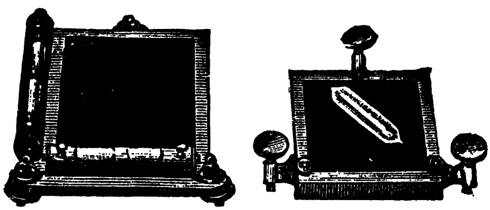


Fig. 33.

Another form of horizon consists of a plane mirror which is adjusted horizontally by means of a spirit level, such an instrument being very cheap and portable.

The Station Pointer is a very useful adjunct of the sextant for coasting or nautical surveying. It consists of three brass arms mounted radially to the centre of a divided circle. The centre arm is fixed at zero, the two outer arms, one left and one right, move round the circle, and can be clamped at any angle from the centre leg. The circle is divided to half degrees, and the divisions are cut

on the brass or on a silver arc let into the brass, in which case verniers are supplied to read to minutes, with a tangent screw for setting the arms more exactly. The diameter of the circle is usually 6 inches. The centre is made with a large hole in the middle to allow of the exact position of the centre point being marked with a pricker or pencil. The arms are chamfered, and it is most important that two should meet together and the other arm be as close as possible to zero. Lengthening pieces are supplied and a magnifying glass for reading the vernier.

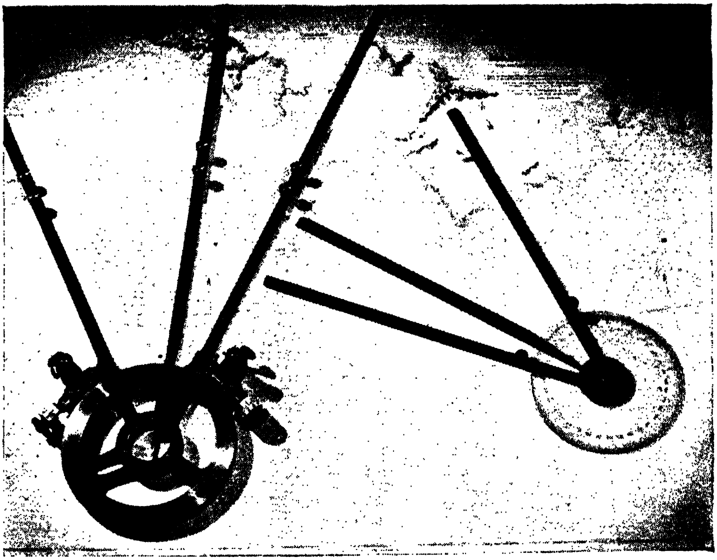


Fig. 34.

A full description of the principle and use will be found in the Admiralty Manual on the station pointer. There are a number of very cheap and useful forms of station pointer.

A number of instruments have been devised to solve the navigational triangle mechanically, but owing to the great precision required in manufacture to give the necessary degree of accuracy, the

cost has hitherto prevented their general use by marine navigators. There is little doubt but that the required solution can be carried out very much more quickly by such a means than by the more laborious methods adopted by the mariner, and the rapid strides made in long distance aviation have caused a demand for such speedier methods.

The Hagner Position Finder is a small, compact instrument of high precision, which may be considered a miniature celestial sphere. It consists principally of a horizon plane, declination arc, latitude arc, altitude arc and hour angle circle.

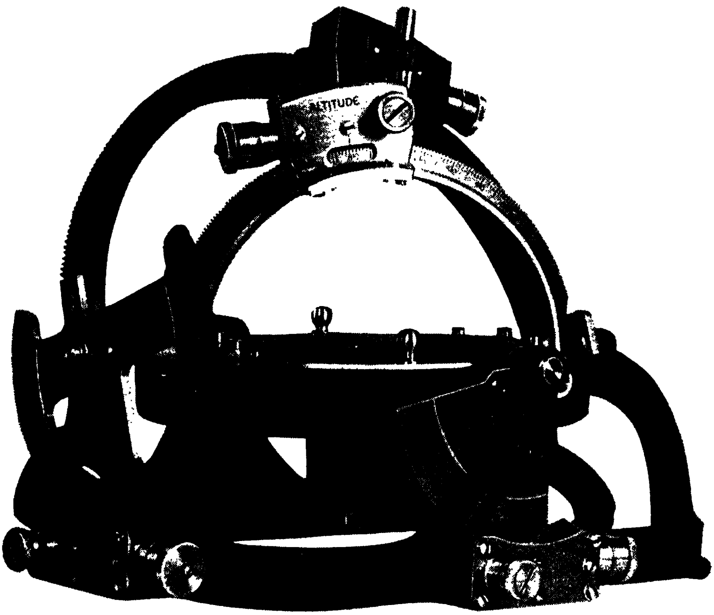


Fig. 35.

The horizon plane carries the altitude arc, azimuth circle and spherical level bubble.

In the centre of the level bubble mounting is located $\frac{1}{8}$-inch diameter circle which is the geometrical centre of the instrument

and corresponds to the observer's position on the Earth when making an observation of the celestial body. The graduated azimuth circle rotates inside the horizon circle which, when the instrument is properly set, gives the azimuth of any heavenly body sighted.

The declination arc is graduated in degrees and pivoted at the North and South Poles of the finder frame. Thus, when the declination of the observed body is set on this circle, the motion of the body across the heavens can be followed by rotating this arc. By reading the hour angle circle which indicates the angular position the exact longitude can be determined.

The latitude arc is a part of the horizon plane and is at all times perpendicular to it. When proper settings are made, the exact latitude of the place of observation can be read directly from the graduated arc. At noon when the sun is at the zenith, the plane of the declination arc and the plane of the latitude arc are one and the same plane.

The altitude arc is mounted on the horizon circle and has its plane perpendicular to it. When the position finder is properly sighted the observed altitude of any body can be read directly.

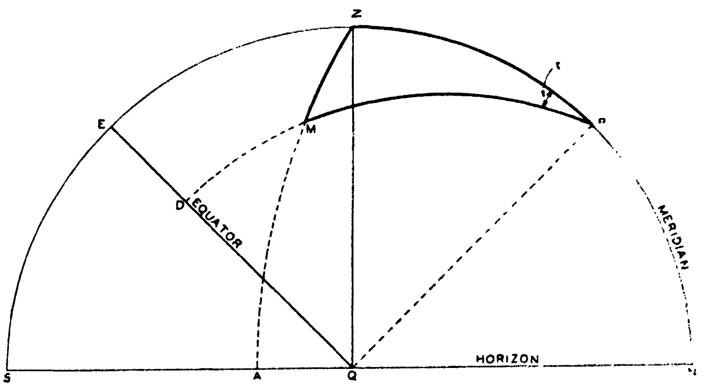


Fig. 36.

A clearer conception of the Hagner position finder and its operation may be obtained from a comparison of the schematic

drawing in Figure 36 and the photograph of the instrument. Figure 36 shows the conventional spherical triangle *P M Z*, the plane of the horizon *N Q S*, and the celestial equator *E D Q*.

P is the elevated pole, *M* is the position of the observed celestial body, *Z* is the zenith of the navigator, and *t* is the hour angle (*H A*) of the observed celestial body. The arc *P M* is the co-declination of the observed celestial body and is commonly called the polar distance. The arc *Z M* is the co-altitude of the observed body and is known as the zenith distance. The arc *P Z* is the co-latitude of the observer. Arc *M D* is the declination of the observed body, arc *Z E* represents the latitude of the navigator and arc *M A* is the altitude of the observed body above the horizon. The arc *P Z S* represents the upper portion of the meridian of the navigator and the arc *P D* represents the hour circle of the observed body.

The data shown in Figure 36 are graphically represented on the instrument as follows:

N Q S is represented by the flat plate of the instrument that carries the bubble and its outer rim is graduated in azimuth.

P is represented by the elevated pole of larger semi-circle that carries the hour angle scale. *M* is represented by the index of the rider which is mounted upon the larger semi-circle that is graduated for declination. *Z* is represented by the 90 degrees graduation on the smaller semi-circle that is graduated for altitude.

The arc *P M* is represented by that portion of the larger semi-circle between the elevated pole and the rider set to the declination of the observed body, when the hour angle of the observed body is set on the hour angle scale of the instrument.

The arc *M Z* is represented by that portion of the smaller semi-circle between the elevated pole and the rider set to the declination of the observed body, when the hour angle of the observed body is set on the hour angle scale of the instrument.

The arc *P Z* is represented by the imaginary meridian of the navigator between the elevated pole of the larger semi-circle and

the 90° degree graduation on the smaller semi-circle, when the latitude of the navigator is set on the latitude scale of the instrument.

The design of the Hagner position finder is such that the instrument can be attached to a tripod when used on the ground. If used in a boat or airplane it can be mounted on a gimbal mount or held in the hand. A 2.5 volt, No. 1 Mazda bulb for illuminating the level bubble at night, is located inside the hand grip. Current for this bulb is received from a 1.5 volt dry cell battery.

The Willis Altitude Azimuth Instrument, the **Spherotrigonometer** and the **Kaster Spherant** are instruments designed on similar lines

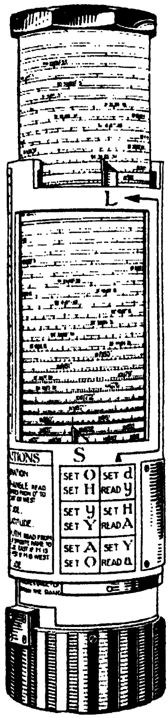


Fig. 37.

to the Hagner, and these are all extremely accurate instruments when used by an experienced navigator.

The Bygrave Position Line Slide Rule is designed to solve the navigational triangle by splitting it into two right-angled triangles. The instrument is of the circular slide rule type, and consists of three concentric tubes, the smallest carrying a long spiral scale of logarithmic tangents. The middle tube carries a spiral scale of logarithmic cosines, whilst the outer tube carries two pointers. By a suitable arrangement of the formulæ, settings can be made on the slide rule so that the calculations can be done in a continuous form, the result obtained being the data necessary for plotting the position from observation of a celestial body, namely, the calculated altitude and the azimuth. See Fig. 37.